December 1994

# Energy & Technology Review

## The National Ignition Facility

University of California
Lawrence Livermore
National Laboratory


## About the Cover

This month's *E&TR* is dedicated to discussions of various aspects of the National Ignition Facility (NIF). The cover features images of the heart of the latest and largest inertial fusion laser being designed by LLNL researchers for use in the international laser science community. In the background on the front cover is an engineering drawing of the 192-beam target chamber where ignition of NIF targets takes place. The inset is an artist's rendering of the NIF in operation. It shows an indirect-drive target contained within a metal cylinder called a hohlraum. The blue laser beams are depositing their energy on the inside of the hohlraum. There the energy is converted to x rays that heat the target intensely, causing it to implode and ignite for a fraction of a second with the energy intensity of the interior of a star. On the back cover is a photograph of an indirect target that contains a tiny amount of hydrogen-isotope fuel. The hohlraum is about 6 millimeters in diameter; the target inside is about 3 millimeters in diameter. The design, manufacture, and testing of these targets by Laboratory scientists is integral to the success of experiments performed on the NIF.

Prepared for **DOE** under contract
No. W-7405-Eng-48

## About the Journal

The Lawrence Livermore National Laboratory, operated by the University of California for the United States Department of Energy, was established in 1952 to do research on nuclear weapons and magnetic fusion energy. Since then, in response to new national needs, we have added other major programs, including laser science (fusion, isotope separation, materials processing), biology and biotechnology, environmental research and remediation, arms control and nonproliferation, advanced defense technology, and applied energy technology, and industrial partnerships. These programs, in turn, require research in basic scientific disciplines, including chemistry and materials science, computing science and technology, engineering, and physics. The Laboratory also carries out a variety of projects for other federal agencies. *Energy and Technology Review* is published monthly to report on unclassified work in all our programs. Please address any correspondence concerning *Energy and Technology Review* (including name and address changes) to Mail Stop L-3, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94551, or telephone (510) 422-4859, or send electronic mail to etr-mail@llnl.gov.

■ December 1994

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Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

UCRL-52000-94-12
Distribution Category UC-700
December 1994

# Energy & Technology Review

# The National Ignition Facility: An Overview

WHEN Secretary of Energy Hazel O'Leary visited LLNL last October 21, she brought a message long awaited by researchers here and throughout the international scientific community. The Secretary announced to an enthusiastic crowd of employees, community leaders, and industry representatives that she had approved "Key Decision 1" to build the National Ignition Facility (NIF) and that LLNL's expertise in laser fusion made it the preferred site for the approximately $1-billion facility.

An international research center comprising the world's most powerful laser, NIF will achieve ignition of fusion fuel and energy gain for the first time in a laboratory. When it begins operation in 2002 (see the box on p. 2), NIF will serve researchers from many different institutions and disciplines for both classified and unclassified projects.

As a DOE–Defense Programs facility, NIF will be a key component in the Department's science-based Stockpile Stewardship Program to ensure the safety and reliability of the nation's enduring stockpile of nuclear weapons. By yielding considerably more fusion energy than is put in by the laser (energy gain), it also will bring us a large step closer to an inertial fusion energy (IFE) power plant. NIF will also advance the knowledge of basic and applied research in high-energy-density science. Finally, the project to construct NIF and equip it with the most modern components will spawn technological innovation in several U.S. industries and enhance their international competitiveness.

If NIF is sited at LLNL, it will be the largest construction project and permanent facility in our history. Scientists worldwide will be performing research here, invigorating LLNL in many existing and new technical areas. Additionally, the project will benefit dozens of Bay Area and California construction and manufacturing companies, creating many new jobs.

NIF is comparable in size to a municipal sports stadium. (See the illustration on p. 9.) The heart of the facility is a neodymium laser system of 192 beams, with each beam optically independent for outstanding experimental design flexibility. Together, the laser beams will produce 1.8 million joules (approximately 500 trillion watts of power for four billionths of a second) of energy. In comparison, LLNL's Nova laser, currently the world's largest, produces 45,000 joules (approximately 15 trillion watts for three billionths of a second).

The beams will compress and heat to 100 million degrees 1- to 3-millimeter-diameter capsules containing deuterium-tritium fuel, thereby producing ignition (self-heating of the fusion fuel) followed by a propagating thermonuclear burn. The implosion process will produce fusion burns with significant energy gain, up to ten times the energy required to initiate the reaction. (See the box on p. 5.)

This sequence of events will produce the equivalent of a miniature star lasting for less than a billionth of a second, yet long enough for researchers to make accurate measurements of its temperature, pressure, and other properties. Indeed, we will "look" at fusion microexplosions with a spatial resolution of 10 micrometers (about one-tenth the size of a human hair) and freeze the action at a time resolution of 30 picoseconds (trillionths of a second).

**Culminates 30 Years of Research**

NIF will represent the scientific culmination of more than 30 years of inertial confinement fusion (ICF) research at LLNL and throughout the world. Calculations by Livermore physicists in the 1960s showed that a laser generating a megajoule of light in ten billionths of a second could ignite a fusion microexplosion in the laboratory. They reasoned that such microexplosions could be used to simulate the detonation of nuclear weapons and that such a fusion technology might one day generate electrical power.

Over the years, Livermore scientists built and operated a series of laser systems, each five to ten times more powerful than its predecessor. (See Figure 1.) Long Path, Livermore's first neodymium glass laser, was completed in 1970 and was our workhorse laser for five years. Our two-beam Janus laser, completed in 1974, demonstrated laser compression and thermonuclear burn of fusion fuel for the first time. In 1975, our one-beam Cyclops laser became operational and was used to perform target experiments and to test optical designs for the future Shiva laser. A year later, the two-beam Argus laser increased our understanding of laser–target interactions.

During this time, laser development and ICF experiments proceeded rapidly at other facilities, including KMS Fusion, the Laboratory for Laser Energetics (LLE) at the University of Rochester, and the Naval Research

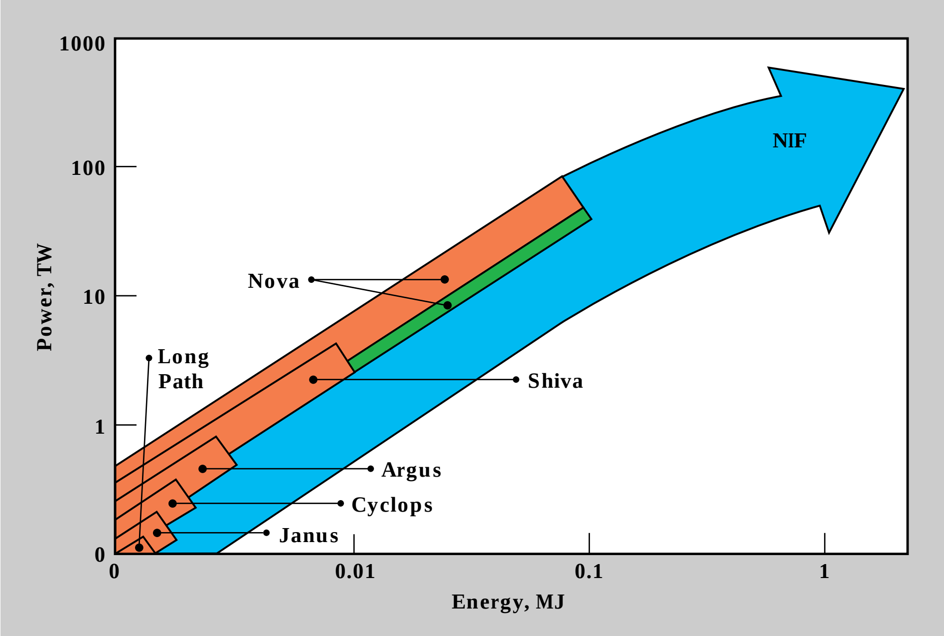



**Figure 1.** **The energy and power of neodymium glass lasers built for inertial confinement fusion (ICF) research at LLNL have increased dramatically over the past two decades.**

## Planning for NIF

The Department of Energy's procedure for approving large projects such as NIF is based on "Key Decisions" (KDs) made by the Secretary of Energy. In January 1993, the Secretary approved KD 0, which affirmed the need for NIF and authorized a collaborative effort by the three DOE defense laboratories and the University of Rochester's Laboratory for Laser Energetics to produce a conceptual design report. This report was completed in April 1994.

KD 1 was signed by the Secretary in October 1994. This decision initiated preliminary design, safety analysis, cost and schedule validation, and a two-year Environmental Impact Statement, which will include public involvement. NIF has been identified as a low-hazard, non-nuclear facility based on the Preliminary Hazards Analysis Report.

In addition, the DOE has agreed to steps before KD 2 that will examine NIF's likely impact on nonproliferation and stockpile stewardship issues. KD 2, scheduled for late fiscal year (FY) 1996, includes detailed engineering design, further cost and schedule validation, and final safety analysis. KD 3, in late FY 1997, will authorize construction and major procurements. KD 4, in late FY 2002, will authorize facility operation and the first experiments.

Detailed planning for NIF has been led by five institutions that have long collaborated on laser fusion experiments: LLNL, Los Alamos National Laboratory, Sandia National Laboratory, the University of Rochester, and General Atomics. The cooperative spirit of the five institutions and their interactions with industry and the public were cited by Vic Reis, Assistant Secretary for Defense Programs, during a visit to LLNL last November.

Laboratory. Major programs in the Soviet Union, Japan, China, Germany, France, and the United Kingdom were established or expanded.

In 1977, the 20-beam Shiva laser was completed. The largest American ICF project at that time, it delivered more than 10 kilojoules of energy in less than a billionth of a second. Meanwhile LLE's 24-beam Omega system became operational in 1980. Novette, which came on line in 1983, was the first laser designed to generate green and ultraviolet light. It confirmed work done at several ICF centers, showing that plasma instabilities were suppressed by shorter wavelength light.

As a result of this work, Nova was redefined as a 10-beam system with frequency conversion rather than the 20-beam infrared system originally approved. Nova became operational in late 1985, the same time that the French Phebus laser, consisting of two Nova-style beamlines, was completed.

Using the Nova and Omega lasers, as well as underground nuclear experiments in the Halite-Centurion Program, scientists have made important progress in understanding ICF. At the same time, the study of scaling glass lasers to systems much larger than Nova provided the technical guidelines for a future system to create target ignition and energy gain. (See Figure 2.) ICF takes its place among decades-long international efforts to reach fusion conditions in the laboratory. Unlike magnetic fusion designs, ICF strives to compress fusion fuel isentropically before raising its ion temperature to ignition levels.

Such an ignition facility was strongly recommended by the National Academy of Sciences and the DOE Fusion Policy Advisory Committee in their 1990 reports and by the DOE Inertial Confinement Fusion Advisory Committee and the JASON Review Committee in 1994. This facility, eventually called the National Ignition Facility, would use improved laser design and engineering as well as advanced optics, laser amplifiers, and frequency converters.

Two conceptual designs for NIF were prepared, one using 240 beams and the other employing 192. As Figure 3 indicates, the smaller and less expensive of these designs adequately meets target requirements, with a safety margin of about two for achieving ignition.

## NIF Benefits

By demonstrating thermonuclear ignition and burn in the laboratory for the first time, NIF will play a critical role in the DOE's science-based Stockpile Stewardship Program. With the end of the Cold War, America's nuclear

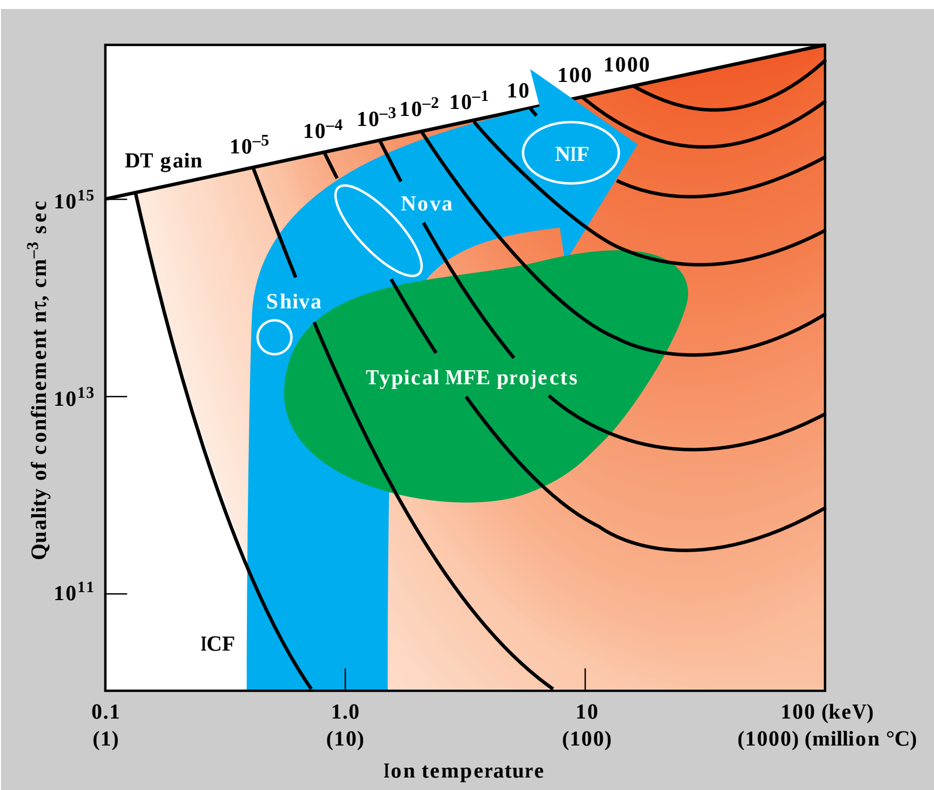



**Figure 2.** NIF will be the culmination of over two decades of research by the international ICF community into the use of glass laser systems to create controlled target ignition and energy gain in the laboratory. Unlike magnetic fusion energy (MFE) designs (e.g., the Princeton Large Taurus, Doublet II, the Tokamak Fusion Test Reactor, and the Joint European Taurus, which trap fuel in an intense magnetic force field to induce fusion), ICF strives to compress fusion fuel isentropically before raising its ion temperature to ignition levels.

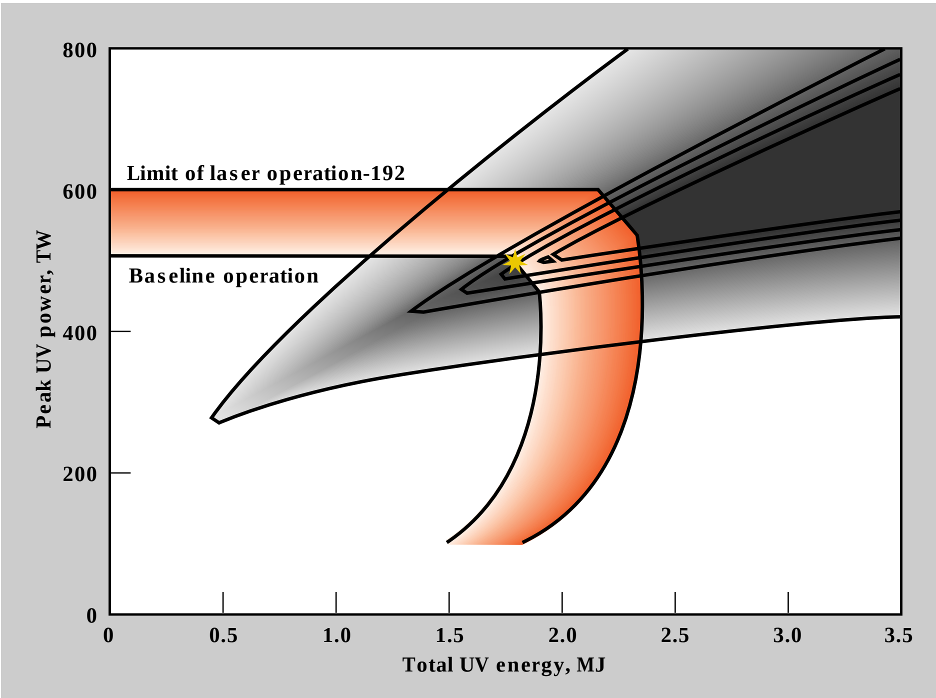



**Figure 3.** Two conceptual designs were prepared for NIF, one using 240 beams and the other employing 192. The smaller of these was chosen because it is more affordable than the 240-beam option. In addition, as the figure indicates, the 192-beam design will not only achieve the baseline operation requirement of 1.8 megajoules and 500 terawatts of power (the optimum point for target ignition indicated by the yellow star), but it can also operate at higher energy and power with increasing risk of damage to the system—up to a maximum acceptable risk or "redline" performance (2.2 megajoules and 600 terawatts). The shaded area indicates the increasing target margin above the minimum power and energy required to achieve ignition.

weapons stockpile is being significantly reduced. However, nuclear weapons will continue to exist for the foreseeable future. In the absence of underground testing, the reliability, safety, and effectiveness of the remaining stockpile can be assured only through advanced computational capabilities and aboveground experimental facilities. NIF is the only facility proposed for the program that addresses fusion and several other physical processes that involve high-energy density.

Data from NIF will complement data from hydrodynamic tests and will also be used to improve the physics in computer codes that are needed to certify the safety and reliability of our remaining stockpile. These more accurate codes will better simulate potential problems in the enduring stockpile as well as improve our interpretation of data from the archives of past underground tests.

NIF will also help to maintain the skills of the nation's small cadre of nuclear weapons scientists and to attract new scientists to help manage

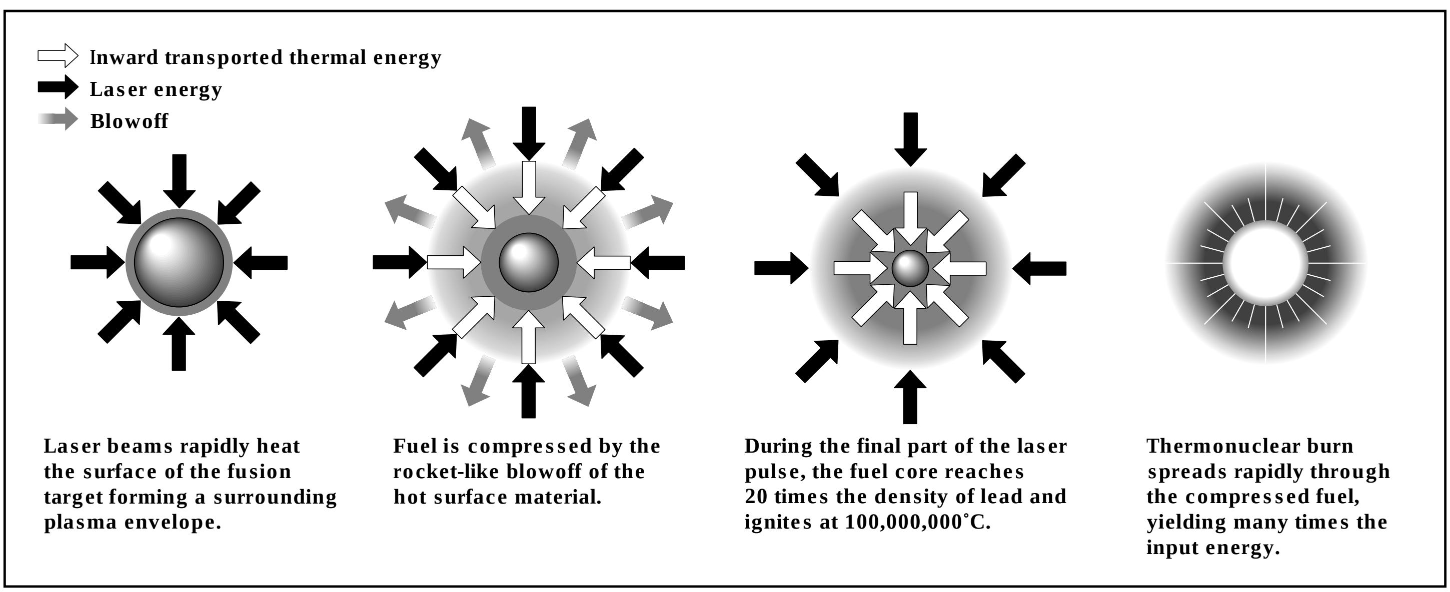



**Figure 4.** The steps of an inertial confinement fusion reaction, which produces up to ten times the energy used to initiate ignition. Under laboratory conditions, the sequence produces energy gain equivalent to the power of a miniature star lasting for less than a billionth of a second.

the Stockpile Stewardship Program, support U.S. nuclear nonproliferation goals, aid in the safe dismantlement of nuclear weapons, and respond to nuclear weapon crises.

Another major goal of NIF is to help establish the scientific basis for environmentally friendly electrical power generated by IFE. The *National Energy Policy Act of 1992* calls for DOE to support both IFE and magnetic fusion energy approaches to achieving fusion energy as a practical power source.

As envisioned, IFE power plants will use high-repetition-rate laser or ion drivers (about 10 pulses per second). The heat from the continual fusion reactions will be absorbed by coolants surrounding the fuel pellets and converted to electricity. NIF will provide crucial data on the design requirements of these drivers and on other critical components. Such data will also be used to help design an Engineering Test Facility that is planned for early next century as the next step toward a functioning IFE power plant.

NIF will also provide new capabilities for the high-energy-density physics community. Because fusion targets will experience temperatures and pressures similar to those found in stars, data from NIF experiments will attract scientists working in such areas as astrophysics, space science, plasma physics, hydrodynamics, atomic and radiative physics, material science, nonlinear optics, x-ray sources, and computational physics. These fields have been the subject of more than 1000 scientific papers published by ICF researchers since 1985.

As the world's largest optical instrument, NIF will spur key U.S. high-technology industries, such as optics, lasers, materials, high-speed instrumentation, semiconductors, and precision manufacturing. U.S. industry has long been a major participant in the rapid progress of ICF research. Today DOE ICF scientists are involved in 24 cooperative research and development agreements (CRADAs) totaling over $160 million in the fields of microelectronics, microphotonics, advanced manufacturing, biotechnology, precision optics, environmental sensors, and information storage.

ICF scientists have also won 26 R&D 100 Awards for outstanding technological developments with commercial application. Most recently, LLNL and Moscow State University received a 1994 R&D 100 award for growing potassium dihydrogen phosphate (KDP) crystals much more rapidly, an achievement with significant promise for NIF.

Much further development in manufacturing technologies over the next three years is needed to meet the cost goals for NIF. For example, the size of NIF optics, such as KDP crystals, is up to two times larger than those used in Nova. In addition, the required damage threshold of these optics is two to three times higher than that of Nova's optics. We are planning a program to

## Inertial Confinement Fusion

Thermonuclear fusion is the energy source for our sun and the stars and for nuclear weapons. In a fusion reaction, nuclei of light elements, such as deuterium and tritium (isotopes of hydrogen), combine at extreme temperatures and pressures to form a heavier element, in this case helium. The energy released in a fusion reaction is about one million times greater than that released from a typical chemical reaction.

There are essentially three methods for confining fusion fuel reactions: gravitational confinement, as inside stars, and magnetic and inertial confinement, which can be achieved in the laboratory. Both magnetic fusion and inertial confinement fusion (ICF) research are supported by DOE.

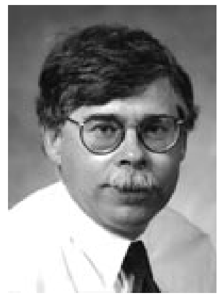
In ICF, energetic driver beams (laser, x-ray, or charged particle) heat the outer surface of a fusion capsule containing deuterium and tritium (D-T) fuel (see Figure 4). As the surface explosively evaporates, the reaction pressure compresses the fuel to the density and temperature required for D-T fusion reactions to occur. The energy released further heats the compressed fuel, and fusion burn propagates outward through the cooler, outer regions of the capsule much more rapidly than the "inertially confined" capsule can expand. The resulting fusion reactions yield much more energy than was absorbed from the driver beams.

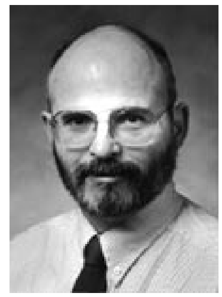
There are two basic approaches to ICF. In the first, called direct drive, laser beams impinge directly on the outer surface of the fusion target. In the second approach, called indirect drive, beams heat the surface of a metal case (hohlraum), causing emission of x rays that strike the fusion target capsule and drive the implosion. (See the box and figure on p. 38, which provide additional information about direct- and indirect-drive targets.)

help our suppliers substantially reduce their costs to manufacture high-quality, state-of-the-art NIF components, an achievement that will help them compete better in the international market.

When the first experiments are carried out on the NIF in 2002, they will begin a new era of advanced research with a laser system so powerful it was only dreamed about several decades ago. By achieving ignition and energy gain for the first time in the laboratory, NIF will maintain U.S. world leadership in ICF research and will directly benefit many different research communities. If sited at LLNL, it will considerably strengthen this laboratory and make it an even greater center of scientific research.

In this special issue of *Energy and Technology Review* dedicated to NIF, we describe in separate articles the importance of NIF to weapons physics and the science-based Stockpile Stewardship in which NIF will play an indispensable role; NIF's potential contributions to energy research; and NIF's likely impact on advancing science and technology. We also describe more fully the NIF facility by taking a tour of it from a laser beam's point of view, and finally, we review the environmental, safety, and health considerations relevant to NIF.





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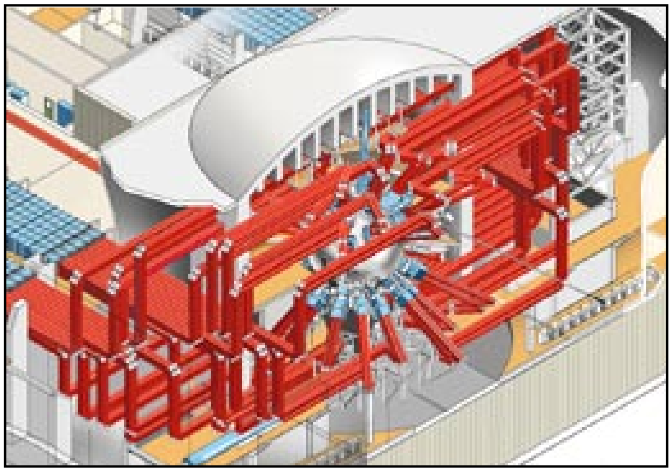
# A Tour of the Proposed National Ignition Facility



***On a conceptual walk-through of the proposed National Ignition Facility, we follow the path of a photon from the master oscillator and preamplifier at the beginning of the laser chain, through the main laser components, to the target. We conclude with the results of our recent Beamlet Demonstration Project, which demonstrated a prototype of one of the 192 laser beams that will be required to achieve ignition and energy gain in inertial confinement fusion targets.***

THE National Ignition Facility (NIF) will house the world's most powerful laser system. Figure 1 is an artist's sketch of the proposed laser and target area building. The overall floor plan is U shaped, with laser bays forming the legs of the U, and switchyards and the target area forming the connection.

The NIF will contain 192 independent laser beams, each of which is called a "beamlet." Each beamlet will have a square aperture of a little less than 40 centimeters on a side. Beamlets are grouped mechanically into four large arrays—or bundles of beamlines—with the beamlets stacked four high and twelve wide, as shown in blue on the left-hand side of the sketch. The 192 laser beamlines require more than 9000 discrete, large optics (larger than 40 × 40 cm) and several thousand additional smaller optics.

The laser output beams strike a series of mirrors, which redirect them to the large target chamber shown on the right side of Figure 1. From switchyards to the target chamber room, the beams are in groups of four (2 × 2 arrays) and follow the beam paths shown in red. At the target chamber, the beams pass through frequency-conversion crystals that convert the infrared laser output beams to ultraviolet laser light. They then pass through lenses that focus the ultraviolet beams on a tiny target located in the center of the target chamber.

To give some perspective on its overall dimensions, the NIF building is roughly 200 meters long × 85 meters wide (about 600 × 250 feet). These dimensions are a little smaller than those of a typical covered football stadium. As an example, Figure 2 compares the NIF building with the Minneapolis Metrodome.

This article takes us on a tour of the proposed facility. First, we follow the complex path of a photon from the master oscillator at the beginning of the laser chain, through the laser components, and on to the target. After this tour, we discuss some of the principal laser components and target experiments in more detail. Finally, we describe the results of the Beamlet Demonstration Project that was recently completed at LLNL. As part of its core activities, the Inertial Confinement Fusion (ICF) Program developed a prototype of a single beamlet of NIF to validate the technology needed for the next generation of glass-laser drivers.

## Master Oscillator

We begin our tour approximately in the center of the facility, where a laser pulse is born in the master oscillator room. Here, four oscillators made of neodymium-doped optical fiber generate weak laser pulses at four separate frequencies (or colors of light). Each pulse is launched into an optical fiber system that amplifies and splits the pulse into 192 separate fibers, 48 of each color. The four colors are used to smooth the intensity (power per unit area) of the laser spot on the target.

The optical fibers carry the laser pulses to 192 low-voltage optical modulators. The modulators for NIF were derived from the integrated-optics modulators that are now being installed in very-high-speed optical fiber communications networks. The modulators allow us to tailor the pulse shape independently in each beamlet under computer control. In this way, the 192 pulses can be carefully shaped and balanced to set up exactly the conditions an experimenter needs on a target without rearranging any laser hardware in the facility. An optical fiber then carries the individually tailored pulse to each beamlet. The power in the laser pulse at this point is a little less than a watt. Typical pulses are a few nanoseconds long

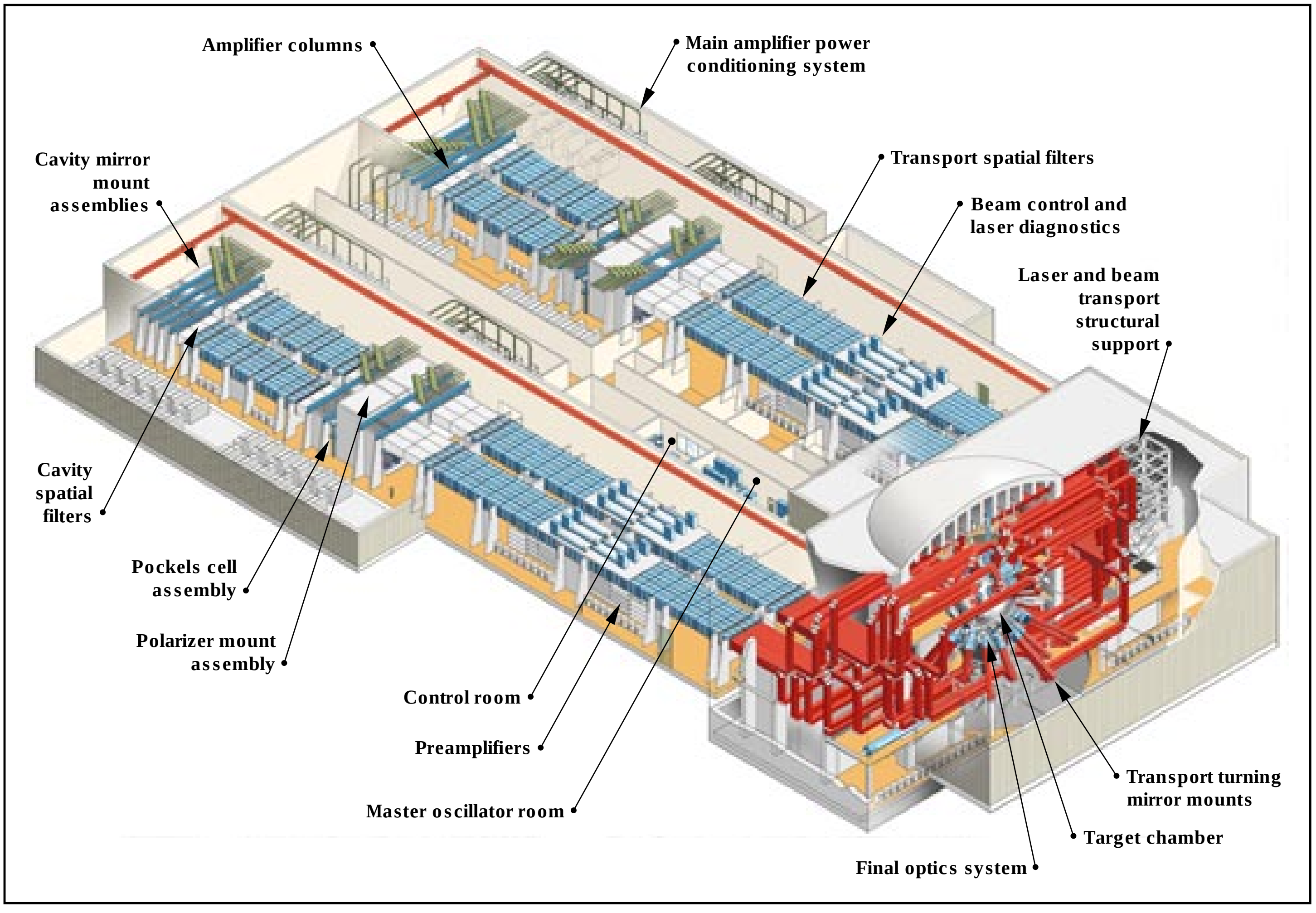



**Figure 1.** View of the proposed laser and target area building for NIF. This facility will contain the world's most powerful neodymium glass laser system, 50 times more powerful than Nova, currently the world's most powerful laser. This sketch shows the laser bays, which form the two legs of the U-shaped floor plan, and the switchyards and target area forming the connection.

(a nanosecond is $10^{-9}$ second), so the energy is a few nanojoules (a nanojoule is $10^{-9}$ joule).

## Preamplifier

Optical fibers carrying the pulses from the master oscillator room spread out to 192 preamplifier packages. As shown in Figure 1, the NIF preamplifiers are located beneath the focal plane at the center of the large transport spatial filters, which are located between the laser components and the target chamber.

Each preamplifier package has a regenerative amplifier in a ring cavity. This device amplifies the pulse by a factor of about a million, from about a nanojoule to a millijoule, with very high stability. The amplifier uses small neodymium glass amplifiers pumped by semiconductor laser diodes so that it has very stable gain and requires little servicing. The laser pulse then enters spatial beam-shaping optics and a flashlamp-pumped, four-pass rod amplifier, which converts it to about a 1-J pulse with the spatial intensity profile needed for injection into the main laser cavity.

## Following a Pulse Through the Main Laser Components

Figure 3 shows the layout of the main laser components of a NIF beamlet. These components take the laser pulse from the preamplifier all the way to a frequency-converted pulse headed to the target. We first follow a pulse through the various components and then discuss their functions in more detail.

A pulse of laser light from the preamplifier reflects from a small mirror labeled LM0 in Figure 3. This mirror is located near the focal plane of the pair of lenses labeled lens 1 and 2 and identified as the transport spatial filter. Light comes to a focus at the focal plane of the transport spatial filter and re-expands to a size of a little less than 40 cm at lens 1 of the spatial filter, where it again becomes a parallel beam. The beam

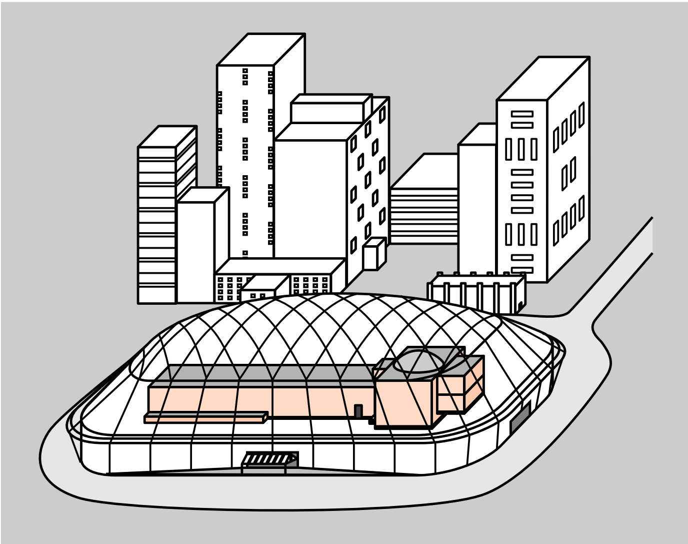


**Figure 2.** The NIF building is similar in size to a modern municipal stadium. For perspective, the NIF building is compared here to the Minneapolis Metrodome.

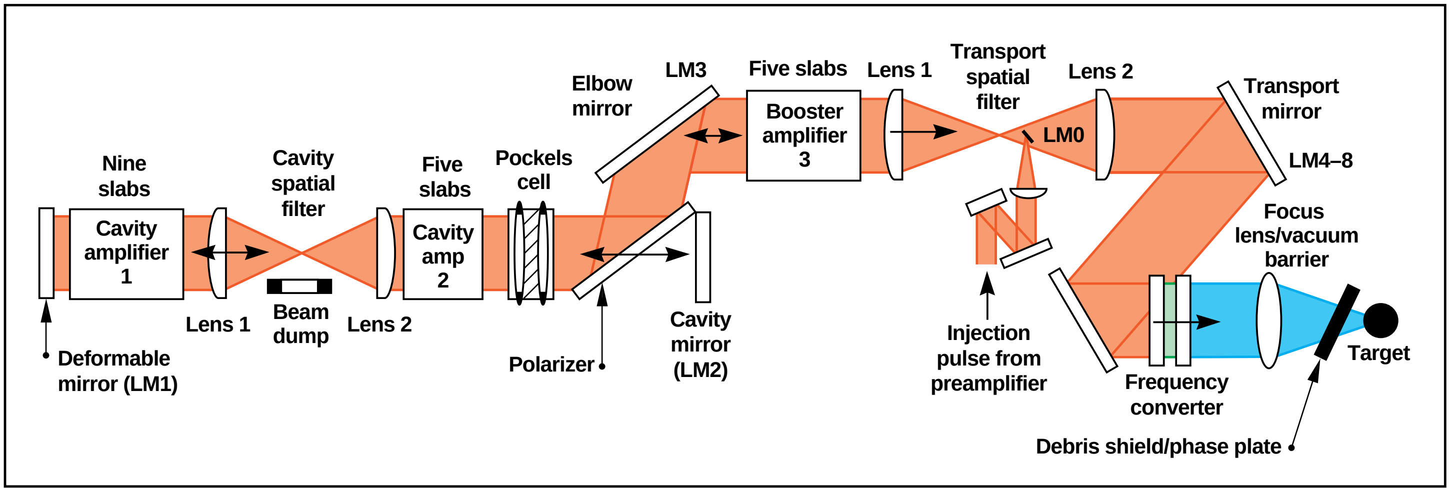



**Figure 3.** One beamlet of the NIF laser, from pulse injection to final focus on the target. We designed the laser chain in this beamline using the CHAINOP family of numerical codes. These codes model the performance and cost of high-power, solid-state inertial confinement fusion laser systems. The path taken by a photon is described in the text.

passes through booster amplifier 3, reflects from the polarizer, is amplified further in cavity amplifier 2, and goes through a second spatial filter identified as the cavity spatial filter. After passing through amplifier 1, the beam reflects from a deformable mirror (mirror LM1 at the far left end of Figure 3). After once again passing through amplifier 1, the beam comes back through the cavity spatial filter and amplifier 2.

Meanwhile, the component identified as the Pockels cell in Figure 3 is energized. This important component rotates the plane of polarization of the laser light from horizontal to vertical. In this polarization, the pulse passes through the polarizer and strikes mirror LM2, which redirects it back once again towards mirror LM1. The Pockels cell rotates the polarization back to horizontal, and the beam passes back through amplifier 2 and the cavity spatial filter and makes another double pass through amplifier 1, reflecting from LM1. It then passes through the cavity spatial filter and amplifier 2 one more time.

By this time, the Pockels cell has been de-energized so that it no longer rotates the polarization of the pulse. As a consequence, the pulse reflects from the polarizer and is further amplified by amplifier 3 to an energy of about 17 kJ for a typical ignition target pulse shape. Now the pulse passes through the transport spatial filter on a path slightly displaced from the input path. Because it is displaced, the output pulse just misses the injection mirror LM0, the mirror where laser light was first reflected when it came from the preamplifier.

The pulse travels through a long beam path reflecting from several transport mirrors until it reaches the target chamber. (For simplicity, Figure 3 does not show all the transport mirrors that will be installed in NIF.) Mounted on the target chamber is a frequency converter that changes the infrared laser pulse to ultraviolet laser light. A focusing lens brings the ultraviolet pulse to a focus at the center of the target chamber. A debris shield protects the focusing lens from any target fragments and may also have a pattern etched into its surface to reshape the distribution of laser intensity in the focal spot on the target.

Four pulses from different beamlets, each at a slightly different color or frequency, come to a focus at a single spot on the target. The intensity profile of the sum of these four spots is much smoother than the profile of each spot individually. Smooth intensity profiles lead to better-understood experimental conditions and better target performance.

An important feature of NIF is its integrated computer control system. This system uses a high-speed optical fiber network to connect roughly 25,000 control points, sensors, and distributed processors. The items that are controlled by computer include motors and switches for alignment, diagnostic systems for the laser beams, data from target diagnostics, data processing stations, and all other control and information features of the facility.

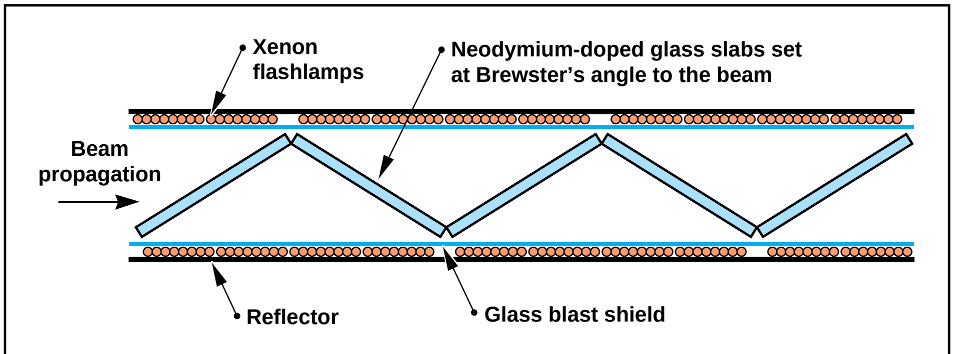



**Figure 4.** **Top view of a large glass amplifier using slabs of neodymium-doped glass set at Brewster's angle to the beam and pumped by xenon flashlamps. The glass blast shields protect the slabs from acoustic disturbances and dirt generated by the flashlamps.**

## More About the Main Laser Components

### Amplifiers

Figure 4 is a top-down view of a glass amplifier. The NIF amplifiers are constructed from slabs of neodymium-doped phosphate glass set vertically on edge at Brewster's angle to the beam. At this angle, horizontally polarized beams have very low reflective losses while propagating through the plates. The glass slabs are $46 \times 81$ cm to give a clear aperture of $40 \times 40$ cm from the beam's point of view.

Figure 5 shows how the amplifier slabs are grouped together into large arrays. Such grouping reduces the number of required parts and floor space, hence the cost of the facility. Long xenon flashlamps extend vertically across a stack of four slabs, an arrangement resulting in a length that is convenient for the pulsed-power system that drives the flashlamps. The width of 12 slabs is convenient for design of the mechanical structures.

The NIF amplifiers are suspended beneath a support frame in order to provide access from the bottom to replace slabs, flashlamps, and blast shields. It is extremely important to minimize contamination of the amplifiers by particles that otherwise might burn into the glass surfaces when illuminated by the intense flashlamp or laser light. Access from the bottom of the amplifiers ensures that service personnel and equipment are always below and downwind from sensitive surfaces, so that dirt falls to the floor and not into open amplifier structures. Figure 6 shows a servicing cart in the process of installing a stack of four laser slabs into the amplifier structure.

The pulsed-power system for the NIF uses advanced self-healing energy storage capacitors developed for use in Strategic Defense Initiative projects. These capacitors store energy at about four times the density and half the cost per joule of conventional capacitors, such as those used in the Nova laser facility at LLNL.

The number of amplifier slabs and their distribution among the three amplifiers were chosen to maximize the output power of the laser over the desired range of pulse shapes. For short pulses, the limit is set by nonlinear effects in amplifiers 2 and 3. For long pulses, the limit switches over to nonlinear effects in amplifier 1 and the limit set by the total amount of energy stored in the slabs. We might have eliminated amplifier 3 and placed 9 or 11 slabs in the amplifier 2 position. However, the polarizer coating suffers optical damage at a rather low fluence (energy per unit area). Such damage limits the laser output fluence to significantly less than we can run with the configuration shown in Figure 3. Notice that amplifier blocks are restricted to have an odd number of slabs (see Figure 4) so that gain gradients in the end slabs cancel.

## Spatial Filter

The NIF has two spatial filters in each beamline. In essence, a spatial

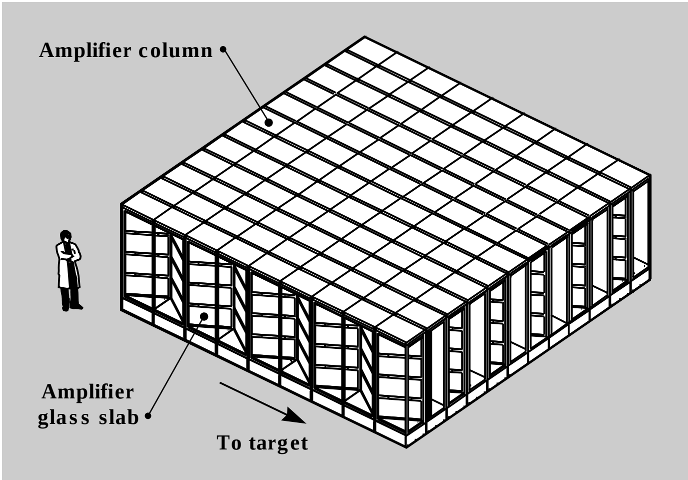



**Figure 5.** The main cavity amplifier assembly is typical of all the NIF amplifiers. Notice that a column consists of an amplifier that is 4 beams high. Groups of columns that are 12 beams wide form an amplifier assembly.

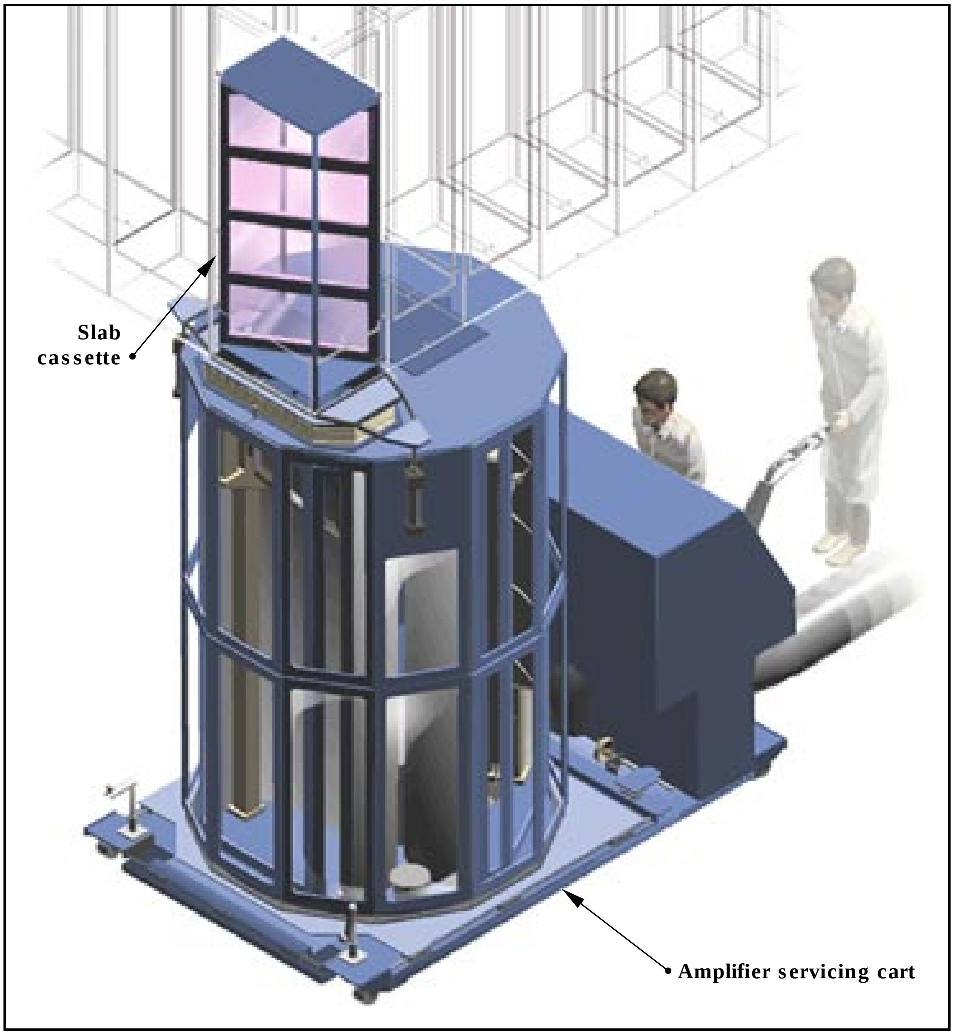



**Figure 6.** To facilitate maintenance, the slab and flashlamp cassettes shown at the top will be changed from underneath an amplifier column using a special cart. This approach will allow the critical amplifier components to be protected from the laser bay environment at all times.

filter—or image relay pair—is a pair of lenses separated by the sum of their focal lengths. A parallel beam incident on one lens comes to a focus in the center and emerges as a parallel beam at the other lens.

Spatial filters serve several functions in large lasers. For NIF, we positioned a pair of lenses so that an image of the very clean intensity profile injected from the preamplifier reforms near the amplifiers and at the frequency converter. Diffraction causes intensity noise to grow in laser systems, but this growth is reset to zero in the vicinity of an image of the original input profile. In addition, nonlinear effects in the laser cause small-scale intensity noise in the laser to grow, but this small-scale noise comes to a focus displaced to the side of the main focus in the spatial filter. This displaced focus means that we can place a small pinhole at the focal plane that blocks this noise while allowing the main beam to go through. In addition, the focal plane inside the spatial filter gives us a convenient location for injecting the input pulse from the preamplifier without requiring any additional, expensive, large-aperture optical components.

Because the intensity near the focal plane is very high, the spatial filters in large lasers such as NIF must be operated in a vacuum. Figure 7 shows the large transport spatial filter vacuum vessel for NIF. The cavity spatial filter is similar, but somewhat shorter.

### Pockels Cell and Polarizer

A Pockels cell uses electrically induced changes in the refractive index of an electro-optic crystal, such as KDP (potassium dihydrogen phosphate or $KH_2PO_4$) to rotate the polarization of light. When combined with a polarizer, the Pockels cell can serve as an optical switch that directs light into one or the other of two possible paths, and it is used for this function in the NIF laser.

Conventional Pockels cells require a crystal that is roughly the same thickness as the beam diameter. A crystal this thick is completely impractical for the NIF's 40-cm beam. Instead, the Pockels cell used in the NIF laser is a new type developed at LLNL. As shown in Figure 8a, it contains a thin plate of KDP placed

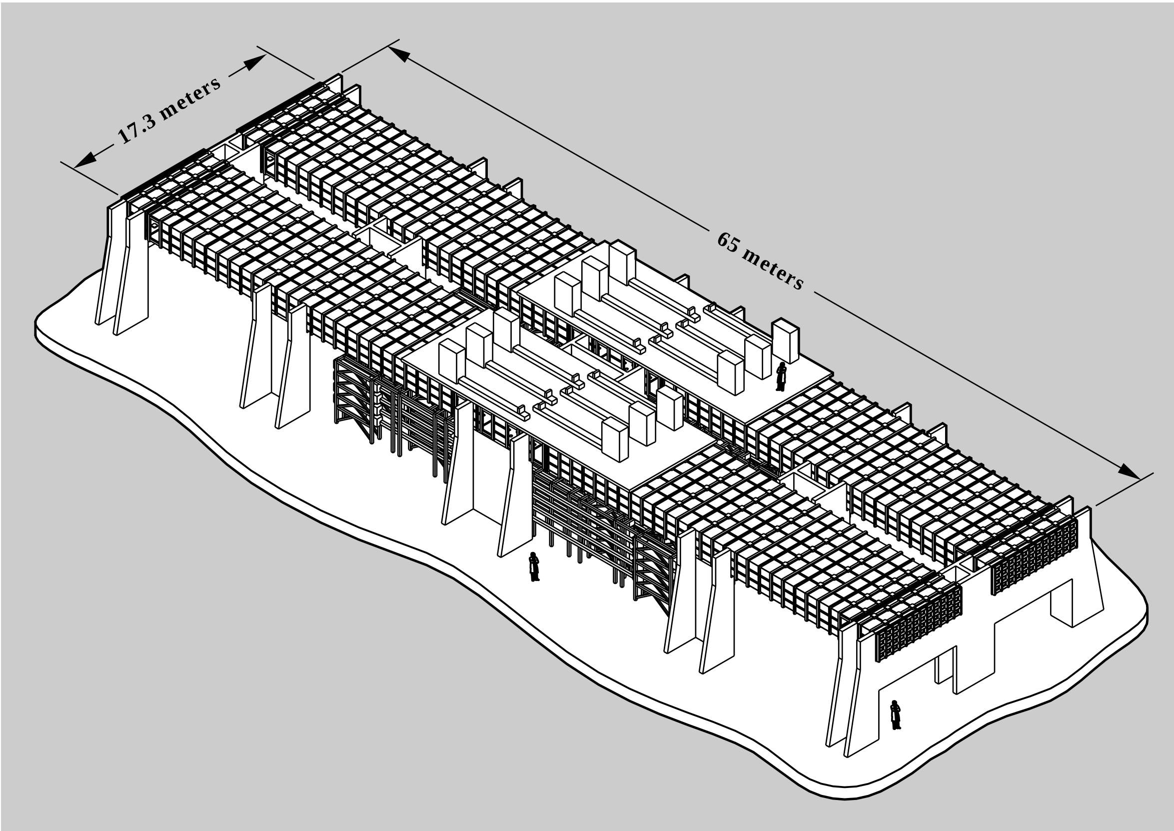



**Figure 7.** **Spatial filters in large lasers must contain a vacuum. Shown here is the transport spatial filter vacuum vessel for NIF. The basic functions of the transport spatial filter and cavity spatial filter are similar, but their lengths and internal components are different. Each vessel contains 48 beams. The entire structure is supported from the floor by reinforced concrete pillars. The pulse-generation system is located below the center section. Laser diagnostic units are supported by a frame attached to the filter top. Access to internal mechanisms is via doors on the vessel sides.**

between two gas-discharge plasmas. The plasmas serve as conducting electrodes, which allow us to charge the surface of the thin crystal plate electrically, but they are so tenuous that they have no effect on the high-power laser beam passing through the cell. Figure 8b shows a plasma electrode Pockels cell of this sort with a clear aperture of 35 cm. The device is now operating in our Beamlet Demonstration Project at the full laser fluence proposed for the NIF.

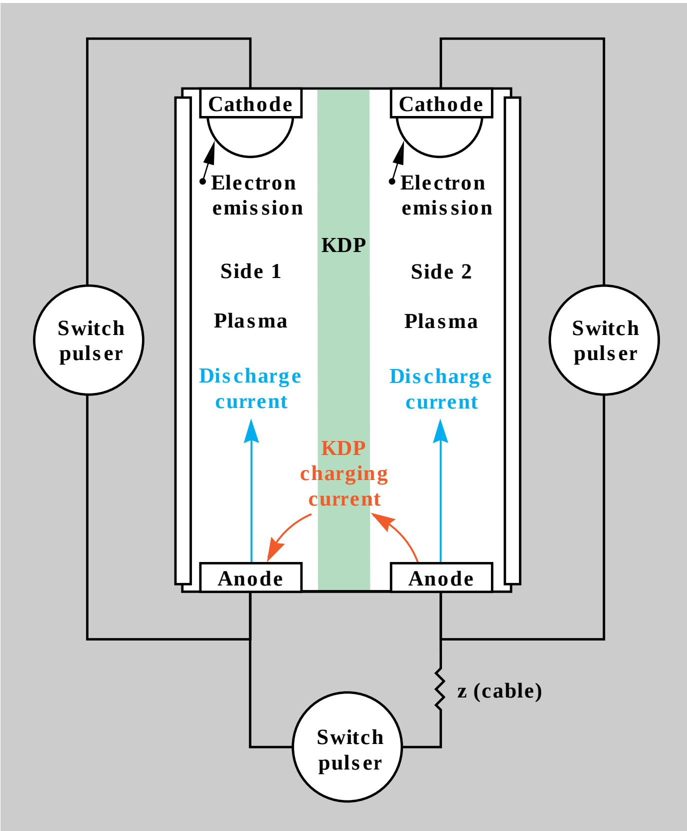
The polarizer for the switch is a multilayer dielectric coating set at Brewster's angle to the beam. These thin-film polarizers are difficult to manufacture, but research supported by LLNL at commercial manufacturers has improved their process control and demonstrates that large polarizers meeting the NIF specifications are now available.

## Deformable Mirror

The NIF laser must have beam quality high enough that it can place all of the energy from each beamlet into a circle of about half a millimeter in diameter at the center of the target chamber. It is possible to purchase optical components finished well enough to achieve this goal, but the cost of fabrication is higher than we would like.

We can use less expensive components if we design the laser to include an adaptive correction system that compensates for distortions in the beam. An adaptive system also allows us to compensate for other important distortions, such as thermal gradients. Recent advances in adaptive optics in the Atomic Vapor Laser Isotope Separation program at LLNL, and at several commercial companies and government research facilities, show that the cost of the deformable mirror, sensor, and processor technology required to

(a)




(b)

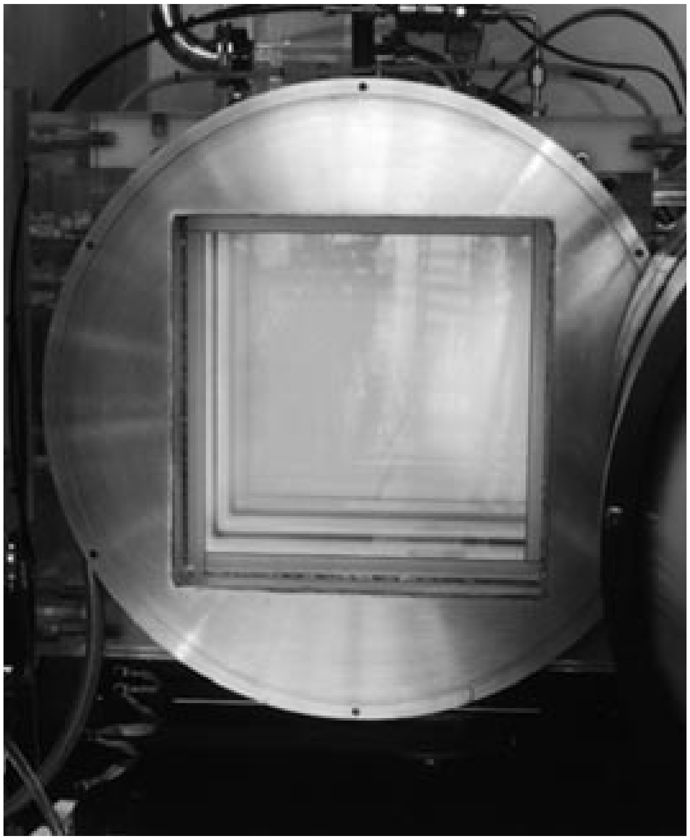


**Figure 8.** **(a) The Pockels cell optical switch. This optical switch uses plasma as transparent, high-damage-threshold electrodes to charge the potassium dihydrogen phosphate (KDP) crystal. (b) A large-aperture, plasma electrode Pockels cell installed in the Beamlet Demonstration Project. Tests show that this device meets the requirements for timing, efficiency, and stability needed for NIF.**

implement such a system has fallen to the point that adaptive correction systems are very desirable for the NIF facility. Figure 9 shows a typical deformable mirror that uses electrostrictive actuators to bend the mirror surface to compensate for wavefront error. This mirror is installed on the Beamlet Demonstration Project, where we are studying its performance. The NIF will use a similar, but larger, mirror as mirror LM1 in Figure 3.

### Frequency Converter

A neodymium glass laser generates light at a wavelength of about 1 micrometer in the infrared region. However, we know that inertial fusion targets perform much better when they are driven with ultraviolet radiation. The NIF laser will convert the infrared (1.05-μm) light to ultraviolet (approximately 0.35 μm) using a system of two nonlinear crystal plates made of KDP, the same type of crystal that is used in the Pockels cell.

Figure 10 shows the arrangement of the two crystal plates. The first plate converts two-thirds of the incident 1.05-μm radiation to the second harmonic at 0.53 μm. Then the second crystal mixes that radiation with the remaining 1.05-μm light to produce radiation at 0.35 μm. This process has a peak efficiency greater than 80%, and the efficiency can exceed 60% for the complex pulse shapes used to drive ignition targets.

## Target Area and Target Diagnostics

Figure 11 shows an end view of the NIF target area. From this perspective, we can see the beam paths from the laser output through the turning mirror array to the target chamber. The target chamber is a 10-m-diameter aluminum sphere. The beams enter the chamber in two conical arrays from the top and two from the bottom through final optics packages mounted to the target chamber. Figure 12 shows a final

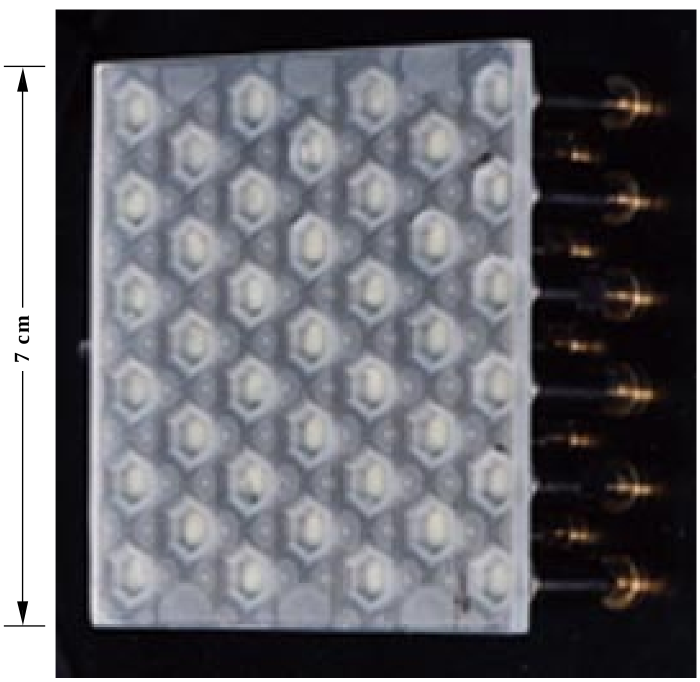



**Figure 9.** The cavity mirror farthest from the target area (LM1 in Figure 3) is a deformable mirror used for performing wavefront corrections of the beam. Electrostrictive actuators bend the mirror surface to compensate for wavefront error. This photograph shows a 70- ¥ 70-mm deformable mirror currently used on the Beamlet Demonstration Project. The NIF will use a mirror that is similar to this one, but larger.

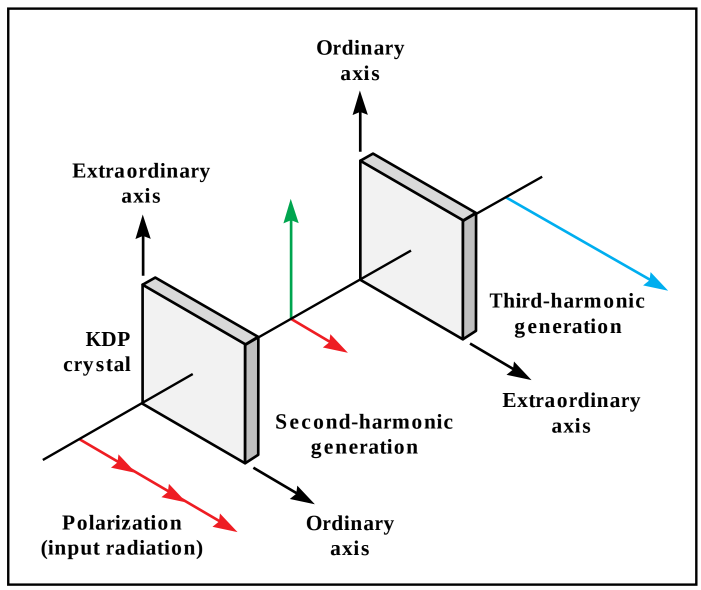



**Figure 10.** The NIF configuration for frequency conversion to the third harmonic using two KDP crystal plates. The NIF laser generates light in the infrared region (this 1.05-μm wavelength light is shown as red in the drawing). However, inertial fusion targets perform better with ultraviolet radiation. This 0.35-μm wavelength light is called the third harmonic (shown as blue). The first KDP crystal (left) converts two-thirds of the input radiation (red) to second-harmonic radiation (green). The second crystal mixes the remaining input radiation with the second harmonic to produce third-harmonic radiation (blue). Peak conversion efficiencies can exceed 80%.

optics assembly subsystem. Diagnostic instruments, such as x-ray spectrometers, microscopes, and cameras, are mounted around the equator and at the poles of the target chamber.

Figure 13a is a scale drawing of a typical fusion ignition target that will be used with this chamber. The target is a metal cylinder—typically made of gold or lead—about 6 mm in diameter and 10 mm long. It contains a plastic fusion capsule about 3 mm in diameter. The capsule is chilled to a few degrees above absolute zero and is lined with a layer of solid deuterium–tritium (DT) fusion fuel. The hollow interior contains a small amount of DT gas.

Figure 13b is an artist's 3-D rendering showing how laser beams deposit their energy on the inside surface of the metal cylinder or "hohlraum" where the energy is converted to thermal x rays. The x rays heat and ablate the plastic surface of the ignition capsule, causing a rocket-like pressure on the capsule and forcing it to implode.

Figure 14 is an x-ray image of a target shot from the Nova laser showing the glowing spots where Nova's ten beams strike the inside surface. In this image, artists drew in the laser beams and the outline of the cylinder, which are invisible in an x-ray photograph. For this experiment, the metal wall was made thin enough that some of the x rays leaked through to be photographed. Thicker walls are used for most targets. In the language of fusion research, this target is called an "indirect-drive" target because the

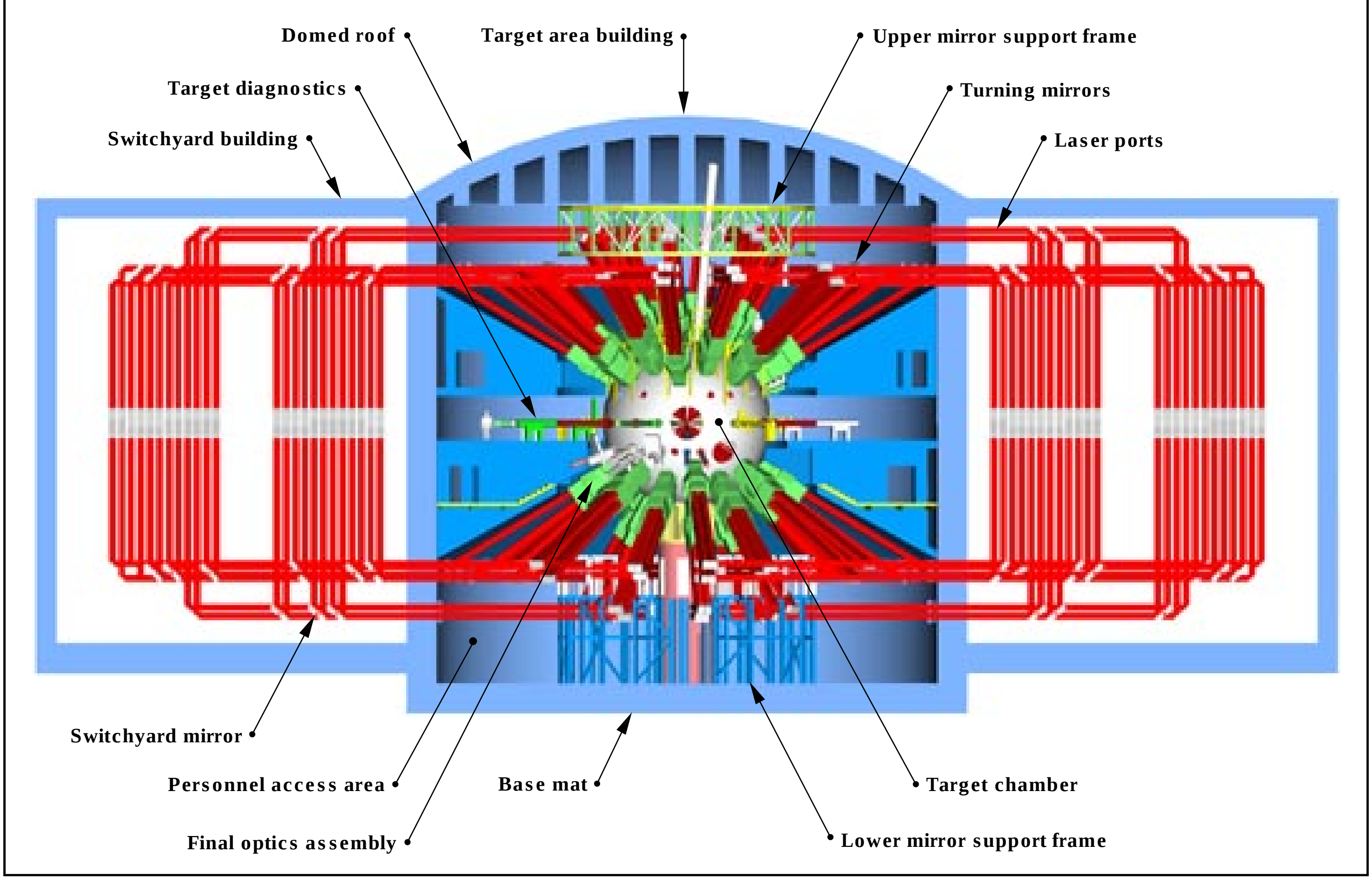



**Figure 11.** Cut-away view of the NIF target area showing the major subsystems. The laser beams focus energy onto a target located at the center of the target chamber, which is housed in a reinforced-concrete building. Target diagnostics mounted on the chamber will collect the experimental data.

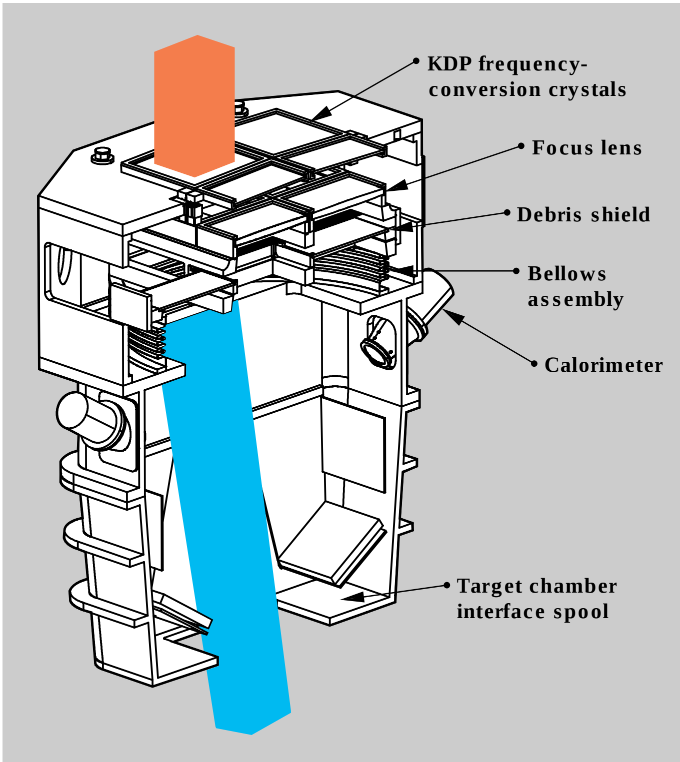


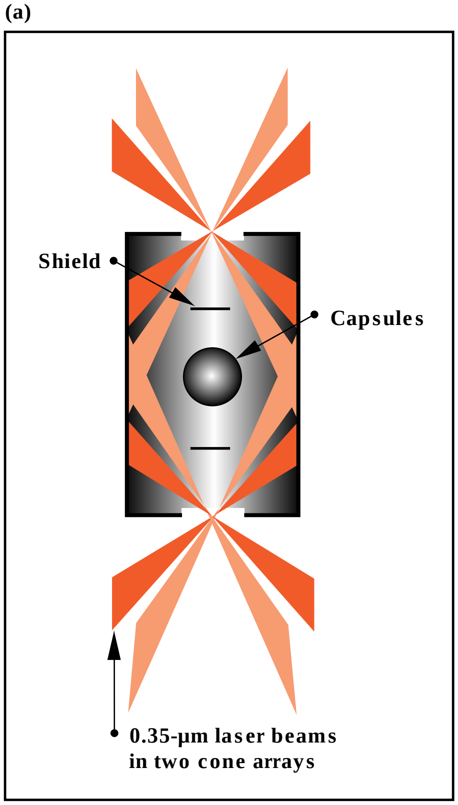

**Figure 12.** The final optics assembly is a single, integrated structure that is mechanically supported by and fastened to the target chamber. The frequency-conversion crystals (see Figure 10) are shown at the top. This system will convert four infrared beams to the third harmonic, focus the beams onto a target, and provide beam smoothing and color separation. The calorimeter is used to obtain energy measurements on the incident beam.

laser beams do not strike the fusion capsule directly. NIF can also study "direct-drive" targets in which there is no hohlraum and the beams do strike the capsule directly.

To illustrate the type of diagnostics we use to study fusion targets, Figure 15 shows a sequence of pictures of a fusion capsule implosion from a direct-drive target on the Omega laser at the University of Rochester. Here, the fusion capsule is similar to, but smaller than, the one shown in Figure 14. (Indirect-drive targets give similar pictures, but the hohlraum and other complications make the pictures less clear.) The images are from an x-ray framing camera microscope (that is, the sequence of frames was taken by a very-high-speed motion picture camera). Each frame lasts for 50 picoseconds (50 trillionths of a second).

**Figure 13.** (a) Scale drawing of a typical fusion target. The outer metal cylinder, usually made of either gold or lead, is about 6 mm in diameter. Inside is a plastic fusion capsule that is about 3 mm in diameter. The capsule is lined with a layer of solid deuterium–tritium (DT) fusion fuel, and the hollow interior contains a small amount of DT gas. Laser beams enter the target in two conical arrays. The outer and inner cones are shown at the top and bottom of the target. (b) An artist's 3-D rendering of the laser beams depositing their energy on the inside surface of the hohlraum where they are converted to x rays that heat the target internally, causing it to implode and ignite.

(a)

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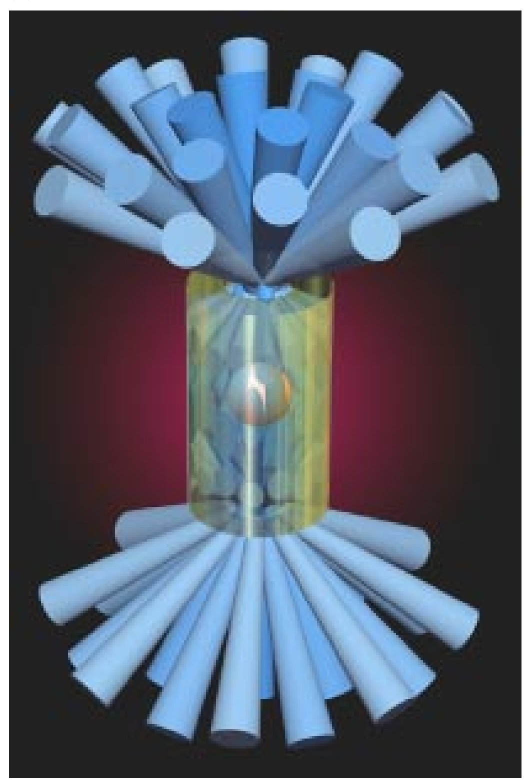


In Figure 15a, the 0.25-mm-diameter capsule lights up brightly as the laser beams first strike its cold surface. In the next several frames, the surface of the capsule blows outward, and the gas fill is accelerated towards the center, compressing to a very high density. In Figure 15g, the gas begins to collide with other imploding gas at the center of the capsule and comes to a stop. As it stops (or stagnates), the temperature shoots up to a value at which fusion reactions can begin. The high-temperature region at stagnation can be seen as a bright x-ray spot in Figures 15g through 15j. If this were an ignition target shot using the NIF, the hot gas core or “spark plug” would ignite the surrounding, relatively cold DT layer, producing roughly 10 megajoules of fusion yield. The hot target plasma then expands and cools in Figures 15k and 15l.

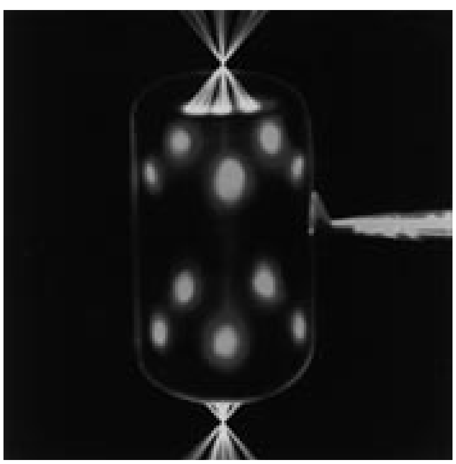


**Figure 14.** X-ray image of a target shot from the Nova laser. The glowing spots are where Nova’s ten beams strike the inside surface of the target’s thin, cylindrical metal wall. This target is called “indirect drive” because the laser beams do not directly strike the inner spherical capsule, which contains DT fuel. The outer shell and beam paths, invisible in an x-ray photograph, are drawn by an artist to show where they were located in the original target.

Ten megajoules is not an enormous amount of energy. It roughly corresponds to the heat released in burning an 11-ounce water glass full of gasoline (about 312 $cm^3$). However, the energy in a fusion target is produced and radiated away in less than a nanosecond from a volume with a diameter of only about a fifth of a millimeter. To do that, the target material must reach conditions that are found in nature only deep within stars and other hot celestial objects or deep within nuclear weapons.

In Figure 15, the drive on the target was deliberately distorted, so the implosion formed a little to the right of center from the camera’s point of view. A perfectly centered implosion gives higher temperatures and better target performance. Nevertheless, these pictures are good illustrations of how target experimenters study the effects of nonideal conditions, such as nonuniform drive pressure, and compare test results to their theoretical models.

## NIF Beamlet Demonstration Project

Glass lasers are a popular and well-known technology, but the NIF laser design is significantly different in many ways from existing large glass lasers (see the box on p. 18). To be quite sure that the NIF system will function as we project, it is prudent to test some of the differences well in advance of construction. In 1992, we

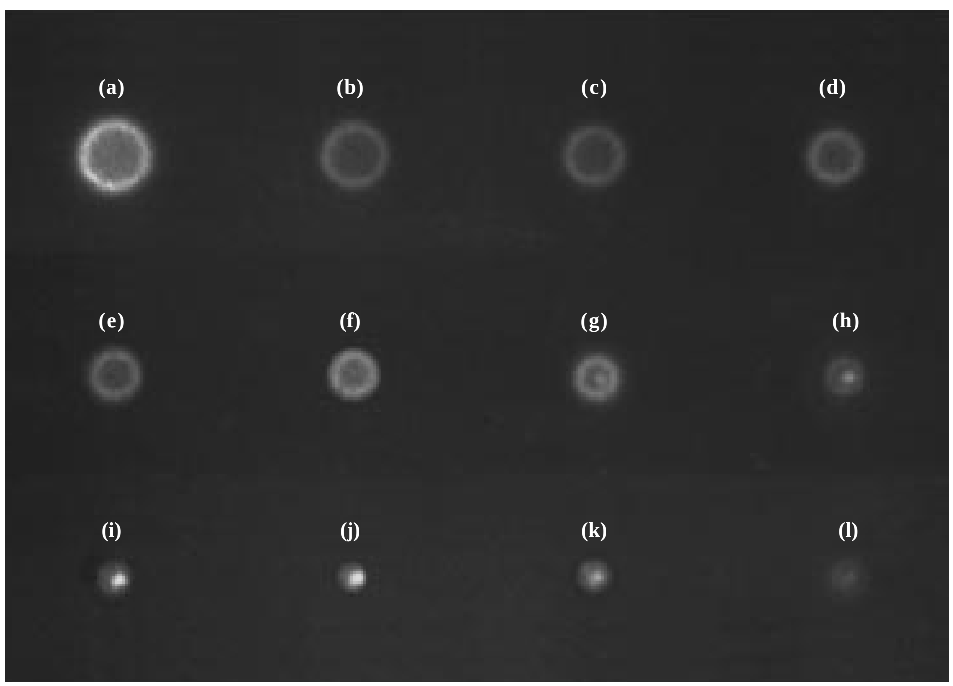


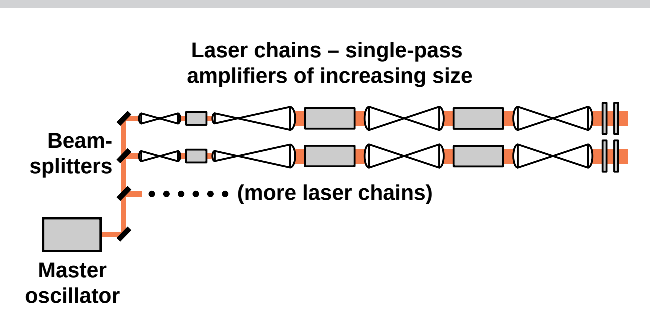

**Figure 15.** Sequence of pictures of fusion-target implosion taken with an x-ray framing camera microscope. Each frame lasts for 50 ps and is a positive image, so bright areas are regions of bright x-ray emission. (a) Laser beams strike the 0.25-mm-diameter cold target shell and start the implosion. (b) through (g) The outer surface of the shell blows off, and the inner part of the shell and gas implode. In (g), the gas fill collides with itself near the center of the implosion, and the rapidly increasing temperature produces a bright spot of x-ray emission. The central hot spot develops through (j) and then begins to expand and cool in (k) and (l).

## How the NIF Differs from Other Glass Lasers

The neodymium glass laser, invented in 1961, was one of the first types of laser to be developed. Researchers quickly realized that it could be scaled up to large beam apertures and extreme peak power. Many laboratories soon began developing glass laser hardware for research on nuclear fusion and other high-energy-density physics.

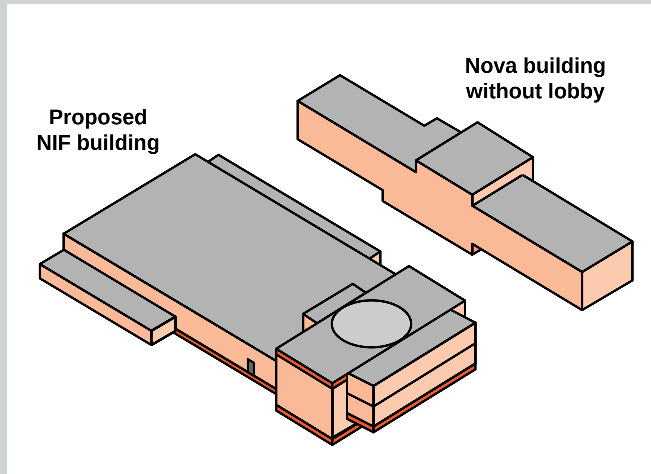
To reach high energy and power, large glass amplifiers are required. However, it is difficult and inefficient to generate a high-quality output beam from large amplifiers. The design that evolved was called the single-pass master-oscillator/power-amplifier (MOPA) chain.

As shown in the illustration below, a MOPA design uses a small oscillator to produce a pulse of a few millijoules with a beam diameter of a few millimeters. After passing through other components, such as a preamplifier, the pulse is divided and makes a single pass through a chain of amplifiers of gradually increasing size. The amplifiers are separate components rather than being grouped in large arrays, as in the NIF design.




The MOPA is a low-risk, but expensive, approach to constructing large glass lasers. Limitations include considerable setup time and cost; very long propagation paths; the need for critical alignments and physical changes to many different components; and the fabrication, assembly, and maintenance of a large number of parts.

The Nova laser at LLNL is the largest operating glass MOPA fusion laser. It contains five sizes of amplifiers with a total of 41 slabs of glass in each of ten laser chains. Compared to the size of the Nova facility, the compact design of the NIF multipass system allows us to put a laser with a typical output that is 40 times larger than Nova's into a building only about twice the size (although the Nova laser does not completely fill the building).




For truly large lasers, such as NIF, the MOPA design has another important disadvantage. The NIF fusion-ignition targets require pulses with a length of 3 to 5 ns. At this pulse duration, we can extract most of the energy stored in the laser glass. When we do, the tail end of a pulse has a much lower gain than the front end, a difference we call saturation pulse distortion (SPD). MOPA designs require larger and more expensive amplifiers and preamplifers under these conditions. Multipass lasers, such as NIF, solve the problem of SPD without the need for larger preamplifiers. In contrast, Nova uses much shorter pulses and does not extract as much of the stored energy.

Even when the Nova laser was designed in 1978, we knew that a multipass design would be potentially much less expensive to build. However, the necessary component development that was still required meant additional risks and possible delays. The NIF laser design is a result of development efforts started many years ago for components such as advanced oscillators, amplifiers, and Pockels cells. Today, our Beamlet Demonstration Project integrates all of these new developments. This effort is showing that the technology has now progressed to the point that a large, multipass glass laser can be built with low risk.

established the Beamlet Demonstration Project (or the Beamlet for short) to test some of the new features. The Beamlet has now been completed and is currently operating reliably up through the frequency converters at fluence and intensity levels projected for NIF.

We built a single prototype rather than a large array of beams because it was clearly much too expensive to construct a full NIF beamline with $4 \times 12$ amplifier blocks and multiple beamlets. We did, however, build the main laser amplifiers as an array stacked two high and two wide because it was important to begin to understand the engineering of large amplifier arrays. To reduce costs, only one of the four apertures in the array contains high-quality laser glass. The other three apertures contain an inexpensive glass that absorbs flashlamp light in a way that resembles the laser glass. In addition, the amplifiers and other laser hardware rest on the floor rather than hanging from a support frame as they will in the NIF design. Components resting on the floor were more convenient for the room we had available, although the system is more difficult to keep clean than that in the NIF design.

The NIF laser design has evolved over the past two years as we try to optimize its cost and match its performance to the wide range of possible experiments that might be conducted. This evolution has led to a few other small differences between the Beamlet and the NIF design presented in the Conceptual Design Report and discussed in the first part of this article. For example, the beam apertures for the Beamlet are slightly smaller than those for NIF, and the laser is shorter. We used 16 rather than 19 slabs of glass, and these slabs are distributed in a ratio of 11-0-5 (eliminating amplifier 2) rather than

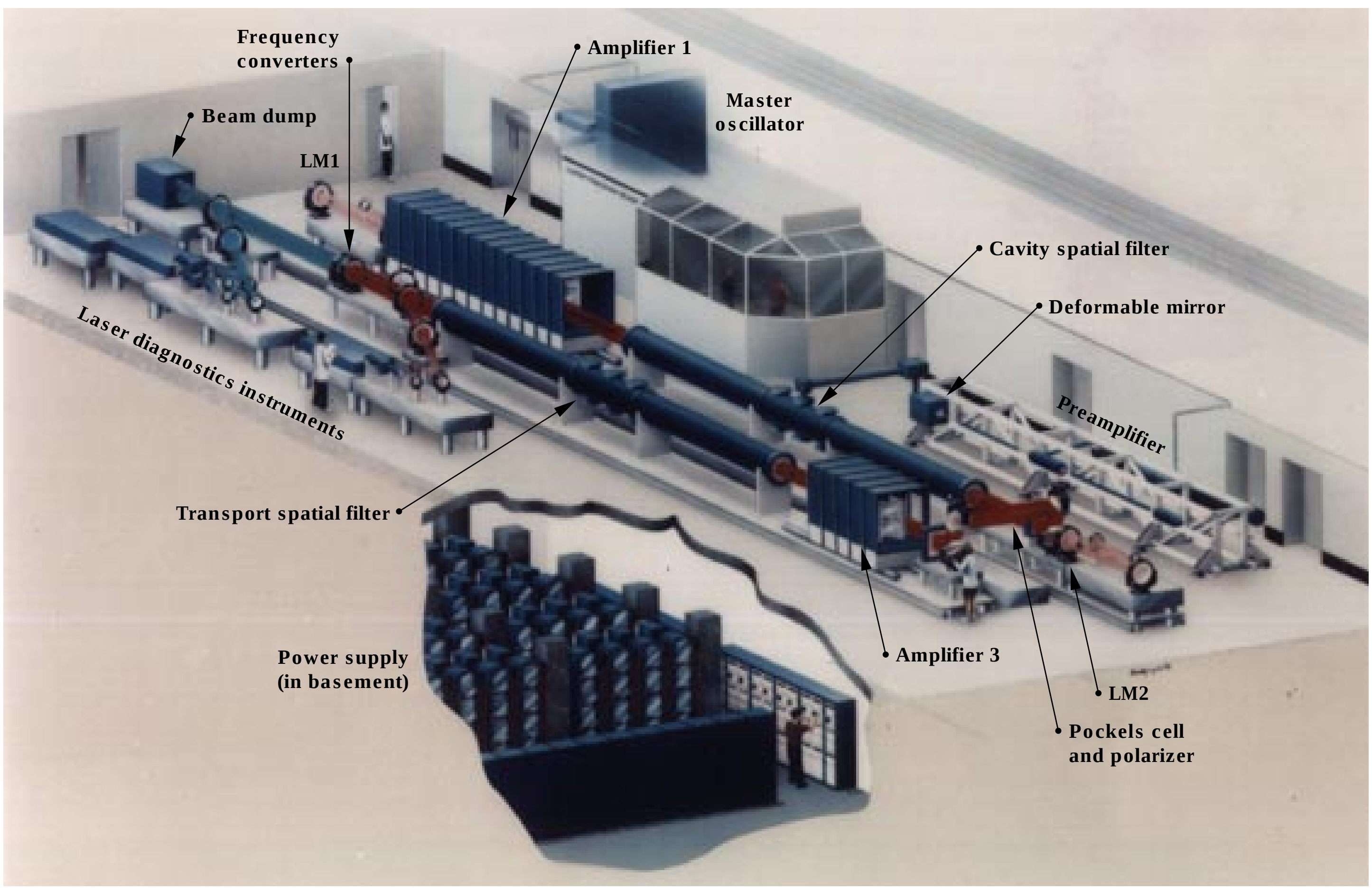



**Figure 16.** The Beamlet is a scientific prototype of the NIF multipass laser. This demonstration unit, which is now operating at LLNL, uses essentially the same technology as that for NIF but with one output channel rather than 192.

9-5-5 in the three amplifiers shown in Figure 4. The NIF distribution gives better performance for pulses of 4 to 5 ns and longer, whereas the Beamlet distribution is better for short pulses. The input pulse from the preamplifier is injected into the cavity spatial filter rather than the transport spatial filter. This design makes the front end slightly larger because the pulse does not see the small-signal gain of amplifiers 2 and 3. However, the design simplifies alignment if the input pulse is used for laser alignment, as it is in Beamlet (but not NIF). Otherwise, the Beamlet has all the NIF components and features shown in Figure 4.

Figure 16 is a drawing of the Beamlet facility. The master oscillator and preamplifier are the same technology as that for NIF, but with only one output channel rather than 192 . The laser pulse reflects from a deformable mirror (see Figure 9) and enters the cavity transport spatial filter. We use a deformable mirror in this position rather than in the LM1 position described for NIF because this smaller mirror could be adapted from an existing design at very low cost. The pulse then passes through amplifier 1 and reflects from mirror LM1, returns through the amplifier and cavity spatial filter to the Pockels cell and LM2, makes a second round trip through amplifier 1, and returns through the Pockels cell to reflect from the polarizer, just as described for NIF.

The output pulse then reflects from three turning mirrors that are used to fold the Beamlet optical path in two so that it fits in the available space. The pulse passes through amplifier 3 and the transport spatial filter, then enters the frequency-conversion crystals. Beam splitters direct samples of the infrared and ultraviolet beams to diagnostic instruments located near the frequency converters. Most of the beam energy is absorbed by an absorbing glass beam dump at the end of the beamline.

Figure 17 is a photograph of the Beamlet amplifier. The amplifier's clear aperture is 39 cm, or essentially the same as the 40-cm aperture proposed for NIF. The amplifiers perform exactly as predicted from design codes (elaborate computer simulations) we developed for smaller amplifiers.

Large amplifier apertures such as this lead to a less expensive NIF because there are fewer beamlets, and many of the costs of a system scale with the number of beamlets rather than their size. However, amplified spontaneous emission causes the gain of large amplifiers to drop by a few percent at the edges of the aperture. We compensate for this gain drop on Beamlet (and NIF) by making the input pulse more intense around the edges.

The large plasma-electrode Pockels cell switch installed on Beamlet is shown in Figure 8b. Only about 30 J leak through the polarizer when we set this switch to reflect 6 kJ from the polarizer, so the Pockels cell and polarizer are remarkably efficient.

Figure 18 shows the infrared output energy from Beamlet as a function of the input energy from the preamplifier. For this set of shots, we set the beam aperture to 34 × 34 cm, a value limited by the 35-cm clear aperture of the Pockels cell crystal. The output energy matches the theoretical model (solid line) very well. We have fired the system at an output up to 13.9 kJ at

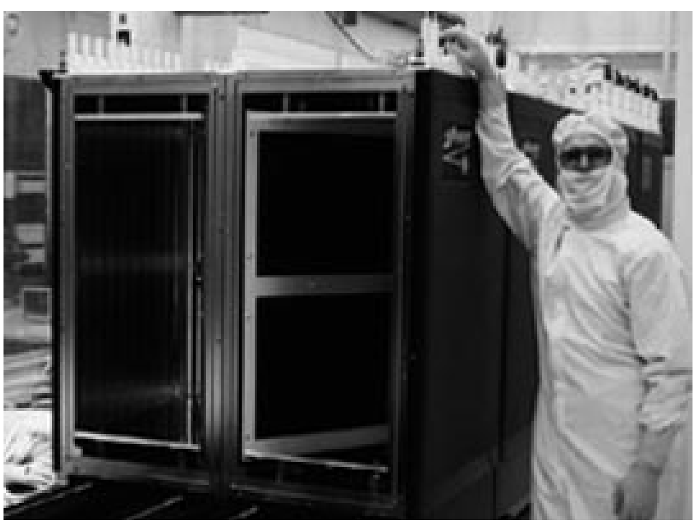


**Figure 17.** The 2 ¥ 2 amplifier module for Beamlet shown during assembly. To reduce costs, only one of the four apertures in this array contains high-quality laser glass. The clear aperture of 39 cm is essentially the same as that proposed for NIF. Such large amplifier apertures lead to a less expensive NIF.

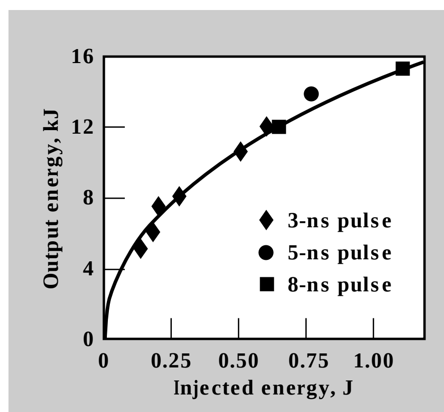



**Figure 18.** Performance of the Beamlet amplifier for a 34- ¥ 34-cm beam at three different pulse lengths. The infrared output energy is plotted as a function of the input or injected energy from the preamplifier. This plot shows that the output energy matches our theoretical model (solid line) quite well.

5 ns and at somewhat higher output for longer pulses. At 5 ns, the fluence (energy per unit area) across the flat-top part of the beam is 14.3 J/cm$^2$. This is about 7% above the nominal operating point for the NIF ignition target in the Conceptual Design Report.

We recently conducted the first series of Beamlet frequency-conversion tests. For these tests, the aperture of the frequency-conversion crystals limited the beam aperture to 29.6 × 29.6 cm. We have operated the conversion crystals up to 8.7 J/cm$^2$ ultraviolet output in 3-ns pulses, which is once again about 10% above the NIF nominal operating point. The conversion efficiency from infrared to ultraviolet was just over 80% for square pulses, as anticipated. The maximum ultraviolet energy demonstrated to date is 6.7 kJ. It is likely that we can operate at somewhat higher fluences, but we will not push beyond the nominal NIF fluences and run the risk of damaging optical components until we have conducted all of the most critical tests on the system. We will certainly have higher energies when we obtain larger crystals and expand the beam size later this year. We will not quite reach the nominal NIF beam aperture of 36 × 38 cm because the Beamlet components are smaller and the beam path is shorter than for NIF. Nevertheless, we should be able to run experiments at apertures of about 34 to 35 cm. We have also run complex shaped pulses of the sort required for ignition targets. In these experiments, we obtained conversion efficiency up to 65% and fluence and energy similar to those for square pulses.

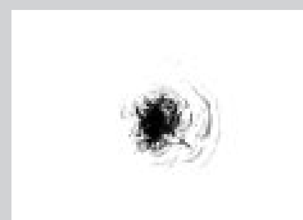
It is important to have very uniform intensity profiles in a fusion laser. Uniform profiles minimize the risk of damage caused by intensity maxima in the beam and help to maintain high frequency-conversion efficiency. Figure 19 shows intensity profiles of the infrared and ultraviolet beams from Beamlet as recorded by television cameras in the laser diagnostics area. The beam profiles are very smooth and flat across the center, as desired, and they roll off smoothly to zero intensity in a small margin around the edge.

Low phase distortions on the beam are also important. Phase distortions not only prevent the beam from focusing on a small spot, but they also degrade the process of frequency conversion. Figure 20 shows the distribution of Beamlet energy at the focus of a lens (in the far field).

## Laser Damage in Optical Materials

When a laser beam strikes a component, it can cause optical-induced damage. The damage usually appears only at high fluence (energy per unit area) and is caused by a small flaw or contamination by foreign material. Flaws or contaminants can absorb enough energy to melt or vaporize and then disrupt the surrounding optical material. The cost of a large laser is roughly proportional to the total beam area, so we push laser designs to the highest fluence that can be tolerated without damage to minimize the beam area and cost.

On the left is a view through a microscope of a tiny light-absorbing defect in a piece of optical glass. This particular defect is about a twentieth of a millimeter in diameter, or about the diameter of a human hair, and it is 10 or 20 times larger than the typical defect that concerns us. When an intense laser beam strikes the defect, its surface evaporates and explodes causing tiny cracks in the glass. As shown on the right, the cracks tend to grow larger with each laser shot, and the damaged spot eventually gets large enough to disrupt the laser beam quality seriously.



In the past 15 years, the number of defects that initiate laser damage in optical materials has decreased dramatically. The decrease is a result of painstaking research at commercial suppliers and various research laboratories. Much of the work was funded by the LLNL laser program and other programs interested in constructing large lasers. As a result, the NIF laser will operate at fluence levels that would have been unthinkable at the time Nova was constructed. As one example, the average ultraviolet fluence at the output of our Beamlet Demonstration Project is more than three times the average fluence that would have been safe for the optical components that were available when Nova was built.

These data reveal that about 95% of the energy is within an angle of ±25 microradians from the center of the spot. Because the NIF requirement for ignition targets is ±35 microradians, this spot meets that requirement. Nevertheless, we would like to improve this value even more because some potential experiments could use a smaller spot.

We obtained the far-field spot in Figure 20 at the end of a sequence that included four full-power Beamlet shots over about 10 hours. Much of the remaining structure in the spot (smaller peaks on the curve) is caused by gas turbulence in the amplifiers and beam tubes. Beamlet's deformable mirror, which was in operation during this test, can correct the long-term thermal distortions in the amplifier slabs very effectively. Indeed, this spot is smaller—by a factor of four or five—than it would be without such correction. However, the deformable mirror system cannot respond rapidly enough to correct for gas turbulence. When the glass amplifier slabs are cold and the temperature is uniform, the deformable mirror has less effect on the spot size, and the spot size is also somewhat smaller than that shown in Figure 20. We have only begun to study the performance of the deformable mirror, but even these early results confirm that adaptive optics will be a highly valuable addition to NIF.

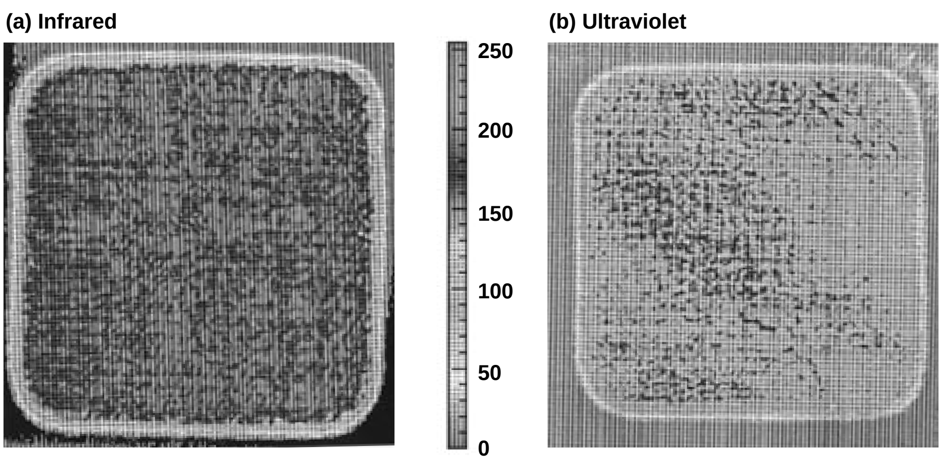



**Figure 19.** **A fusion laser must have uniform intensity profiles. These intensity profiles obtained from Beamlet are smooth and flat across the center during frequency conversion from (a) infrared to (b) ultraviolet light. The small margins indicate that the profiles roll off smoothly to zero intensity around the edges of the 30- ¥ 30-cm beam.**

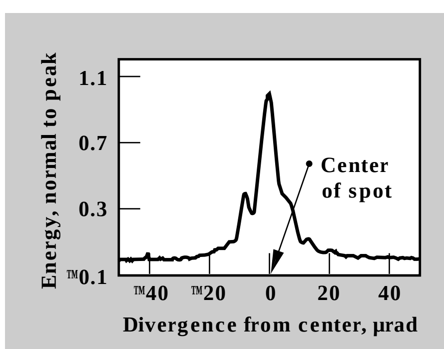
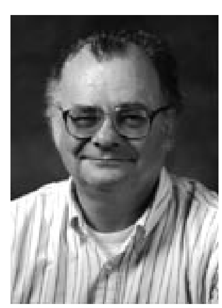



**Figure 20.** **The distribution of Beamlet energy at the focus of a lens (in the far field). This curve shows that about 95% of the energy is within ±25 microradians of the center of the spot, well within the design requirements for NIF ignition targets.**

## Next Steps Toward NIF

Our Beamlet tests to date demonstrate clearly that large, multipass laser systems can operate at the nominal operating conditions proposed for the NIF. We will now proceed to explore more extreme operating conditions and to demonstrate that the proposed target optics will give spots of the desired size and uniformity at the plane of the target in the far field. We will also test many other features suggested for NIF, such as new glass compositions, changes in amplifier pumping conditions, and alternate switch technology. The results from our Beamlet Demonstration Project, along with the models and design codes we are testing, will ensure that we can have great confidence in the performance projected for NIF.

**Key Words:** adaptive optics; Beamlet Demonstration Project; deuterium–tritium (DT) fuel; fusion energy; multipass lasers; National Ignition Facility (NIF); neodymium glass lasers; Pockels cell; potassium dihydrogen phosphate (KDP).



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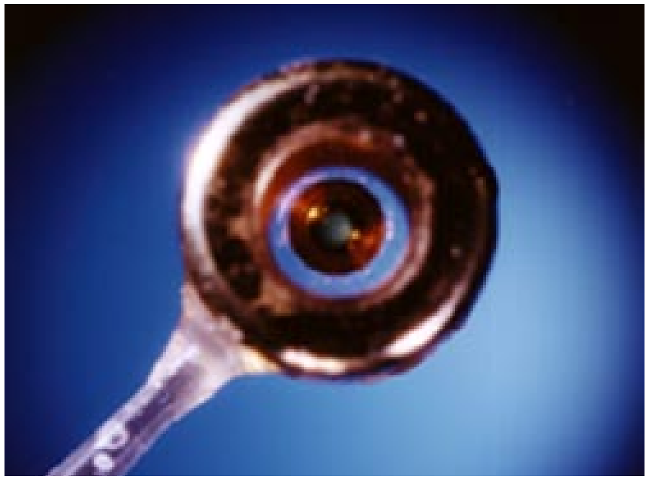
# NIF and National Security



***Although producing total energies that are minuscule compared to those in a nuclear device, the National Ignition Facility will produce energy densities high enough to duplicate many of the physics phenomena that occur in nuclear weapons and will thus help the U.S. to maintain its enduring stockpile of nuclear weapons.***

THE other articles in this issue describe the intended features and capabilities of the National Ignition Facility and the diverse kinds of research that it will support, such as attempts to achieve break-even energy output through inertial confinement fusion (ICF). These other applications are important benefits that derive from the availability of NIF, but here we describe the value of the facility through its key contribution to experimental research in the physics of nuclear weapons. With the moratorium on nuclear testing and the likelihood of a Comprehensive Test-Ban Treaty making such testing permanently unavailable, NIF becomes one of a few means of maintaining and advancing our understanding of the weapons now in the stockpile.

### Stockpile Stewardship

Since the Cold War ended with the dissolution of the Soviet Union, the U.S. nuclear weapons program has changed dramatically. The U.S. brought a unilateral halt to the development and production of new nuclear weapon systems. Also, a moratorium on underground nuclear testing was implemented to further negotiations on a Comprehensive Test-Ban Treaty and to encourage the broadest possible participation in the Nuclear Non-Proliferation Treaty.

A major change in the nuclear weapons program has accordingly been a move from nuclear test-based weapon reliability and safety to reliance on a thorough scientific understanding and better predictive models of performance–that is, science-based Stockpile Stewardship. The Stockpile Stewardship Program is based on several assumptions and observations:

- Nuclear weapons cannot be uninvented and will not go away, even if the U.S. were to dismantle its entire nuclear stockpile.
- U.S. defense policy will continue to rely on nuclear deterrence for the foreseeable future. Therefore, maintaining confidence in the stockpile—in its safety, security, and reliability—is essential.
- The moratorium on nuclear testing will likely be followed by a Comprehensive Test-Ban Treaty, which the U.S. must adhere to while retaining confidence in its nuclear arsenal.

- No new weapons are being developed, and currently there is no known need for future weapon development programs; moreover, some essential facilities of the U.S. nuclear weapons production complex no longer exist.
- The U.S. nuclear stockpile will contain fewer weapons, of fewer types, as well as weapons that will become considerably older than their design lifetimes; this stockpile will require enhanced surveillance and maintenance to recognize, evaluate, and correct problems that may arise.
- There may be a growing need to evaluate potential threats from unfriendly foreign powers and terrorist groups.

We must continue to provide the training and required information for a group of scientists and engineers that will be the stewards for this stockpile under these conditions. The remaining tools at their disposal will have to be used to fill the gaps left by the cessation of nuclear testing. (See Figure 1.)

## Complexity of Nuclear Weapons

Maintaining confidence in the stockpile under the conditions described above is a challenge because of the complexity of nuclear weapons design and of the phenomena that take place when nuclear weapons are operated—chemical explosion, hydrodynamic implosion, mixing of materials, radiation transport, thermonuclear ignition and burn, etc.

Nuclear testing provided a pragmatic solution—integrated tests of the devices—that is no longer available. With the moratorium on nuclear testing, we must rely on advanced computational modeling and non-nuclear experimental techniques for predictions and data.

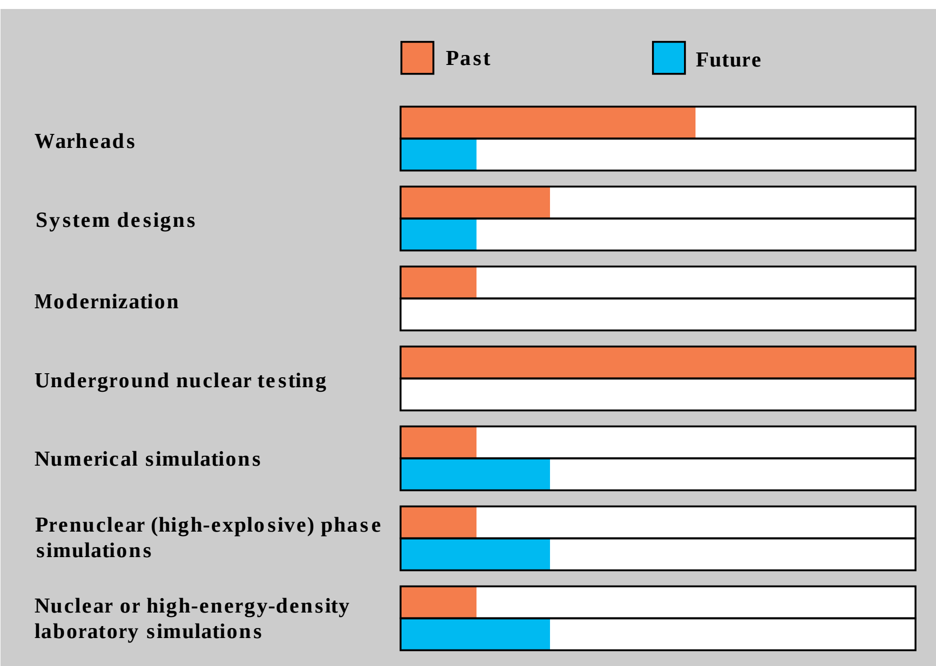



**Figure 1.** Graphic comparison of the situation of the nuclear-weapons stockpile before and after the enormous changes of recent years. The challenge is to maintain confidence in a much smaller stockpile without nuclear testing and modernization.

We do not completely understand the physical processes involved in the operation of a nuclear weapon. Indeed, a complete, detailed, and mathematically exact description of the physics would exceed the capabilities of today's supercomputers. We must therefore make approximations to the physics in our evaluations of performance, although these approximations introduce uncertainties in our predictions. We must rely on our cumulative knowledge, including past test data, to make valid inferences for physics regimes that are inaccessible with current experimental methods.

This expertise is also the only way we now have for the evaluation of many crucial issues, including:

- The severity of age-related material changes discovered through routine stockpile surveillance.
- The severity of unexpected effects discovered with improved computer models.
- Whether retrofits, such as to improve safety or reliability, will function properly.
- Whether new technologies can or should be incorporated in a stockpiled weapon system.

In a nuclear weapon, the phenomena occur in two very different regimes of energy density. In the early phase of the implosion, before the development of significant nuclear yield, temperatures are relatively low. This is the low-energy-density regime; here there is considerable complexity because the strength of the materials and the chemistry of their composition play a role in how events proceed. Full-scale assemblies using mock nuclear material are used to test experimentally the hydrodynamics of the implosion process at the beginning of a weapon's operation. The study of this subcritical regime is carried out at hydrodynamic test facilities using powerful x-ray machines, high-speed optics, and other methods. Current hydrodynamic test facilities can access the precritical physics regime, although, without complimentary nuclear tests, these facilities must be improved to provide much more spatial and temporal information.

After significant nuclear yield begins in a real device and fissile material is heated, we enter the high-energy-density regime. Although no laboratory experiment can duplicate the amount of energy released by a nuclear weapon, many of the physical conditions relevant to such a weapon can be created in the laboratory.

Improving our predictive capabilities for evaluating these processes will be difficult. Without nuclear tests, we can never directly observe the full operation of this high-energy-density regime. We must therefore improve our understanding of the relevant physics with better computations and new experiments, techniques, and facilities. The National Ignition Facility will allow us—on a microscopic scale—to attain the high-energy-density conditions that exist in weapons.

## NIF and Weapons Physics

As a versatile high-energy-density physics machine, the NIF will enable us to gain an improved understanding of the underlying physics and phenomena of nuclear weapons, to acquire and benchmark new data to existing databases, and to test and validate the physics computer codes for ensuring future reliability and performance. The NIF will provide valuable data for predicting the performance of nuclear assemblies and for testing the complex numerical codes used in weapons test calculations.

Creating thermonuclear burn in the laboratory will not only help us to integrate and test all of our physics knowledge but will also help the Department of Energy maintain expertise in weapons design. We envisage training designers both on specific stockpile stewardship issues and on broader NIF ignition questions relevant to inertial confinement fusion.

Weapons research on NIF is driven by a need to acquire a much more detailed understanding of physics processes at high energy densities, as well as by a desire to achieve ignition. We have been studying these processes on Nova and other lasers, but, again, NIF allows us to move our studies into those energy densities that occur in a nuclear weapon.

The maximum total energies available on NIF will be an extremely tiny fraction of the yield of the smallest nuclear weapon (see the box on p. 26); but there are significant benefits to generating so much less energy. The main event of a nuclear test is both extremely brief and extremely violent; it destroys most or all of the diagnostic and measuring instruments. It remains for the researchers afterwards to try to sort out all the physics and phenomena submerged in the event in order to analyze it. By contrast, on the NIF, we can design and perform experiments that isolate whatever physics phenomenon is of interest. We can study the physics at relevant energy densities without having to deal with large total energies. We can thus build an incremental, exact description of the cumulative physics that would make up a nuclear event.

In the high energy densities at which thermonuclear reactions occur, several distinctive phenomena predominate: very high material compressions; unstable, turbulent hydrodynamic motion; highly ionized atoms with high atomic numbers (high-$Z$ atoms); and radiation important in energy transport. These phenomena occur in such astrophysical realms as stellar interiors, accretion disks, and supernovae (and occurred in the Big Bang), but on Earth they occur only in machines such as NIF (and formerly in testing environments created in the areas surrounding nuclear tests).

The weapon physics research program at the NIF will stress investigations of these phenomena, including:

- Material equation-of-state properties.
- Unstable hydrodynamics.
- Radiation flow, including the opacity of ionized elements and x-ray production.
- Nonequilibrium plasma physics, including short-wavelength lasing.
- Thermonuclear burn in the laboratory.

The NIF will have the capacity for doing systematic, well-characterized experiments because of the flexibility of its multiple beam configuration. Considerable experience in doing such experiments very successfully on Nova and other lasers will carry over to the NIF. Laser experiments on the NIF, like those on Nova, can be directly or indirectly driven. In direct drive, multiple beams are directed at the target. In indirect drive, a set of laser beams is directed into a hohlraum, which is a tiny, hollow cylinder (see Figure 2) made of a high-$Z$ material such as gold. The beams enter through the open ends and strike the inner walls, where they are absorbed and generate x rays that heat the interior of the hohlraum. The target is then bathed in this relatively uniform radiation field that heats it to the desired temperature.

In either direct- or indirect-drive experiments, a second set of laser beams prepares a backlighter that produces x rays that probe the target

## NIF: High Energy Density at Low Total Energy

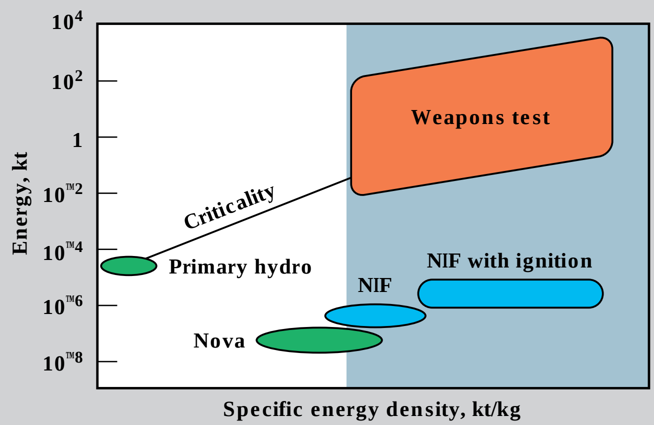
The NIF will provide the high energy densities that are needed for thermonuclear reactions to occur. High energy density, however, should not be confused with high total energy. The two measures are independent: there can be high total energy with low energy density, and high energy density with low total energy. Energy density is the amount of energy per particle, or per unit of volume.

The NIF will operate at low total energies. High energy densities can be produced on a small scale, and in the case of the NIF, the scale is about a millimeter. This fact is vividly evident in Figure 2, which shows a Nova hohlraum compared to a human hair; the large hohlraum used on NIF will be no larger than a dime. A DT-filled capsule of the sort used for ignition studies on the NIF is very small—some 2 to 5 mm in diameter, a tiny fraction the size of a thermonuclear secondary. Thus, although the energy density—the energy per particle—in such a capsule is comparable to that in a thermonuclear secondary, the total energy is minuscule. Ignition on the NIF will have roughly the same explosive force—that is, total energy—as a gallon of gasoline.

The accompanying figure shows the importance of the difference between the two measures of energy. The figure plots energy density versus total energy for laser facilities, such as Nova and NIF, as well as that achieved in a weapon test. Two regions are shown for NIF—without ignition and with ignition. This distinction reflects the two alternative modes in which NIF will be used for experiments in physics related to weapons. NIF without ignition is characterized by the types of experiment described in this article. These experiments do not use fuel-filled capsules; instead, the targets are foils and other materials that enable us to study the behavior of materials and media in the extreme conditions heated by x rays to high energy densities.

NIF with ignition characterizes experiments in which the target is indeed a DT- or fuel-filled capsule, and the calculated energy densities are those predicted to be achievable in the different regions of a burning DT capsule.[1] Because the energy densities achieved in both modes of NIF operation—with and without ignition—show significant overlap with the energy density regime available from weapons tests, NIF can be used to investigate the high-energy-density physics subprocesses that occur in that regime.

Nevertheless, physics investigations on NIF rely only on high energy density (i.e., how dense and hot we can make a relevant target), not on total energy. (The total energy is only high enough to heat or drive a target that is big enough to yield measurable results.) The second, related, point is that the NIF or any other AGEX (above-ground experiment) facility cannot conduct integrative weapon tests because its total energy falls many orders of magnitude short of that regime. NIF cannot be used as a testbed for weapon development. Our analysis of stockpile questions will therefore rely on computer calculations to put together different parts of the physics that we study on NIF.




**NIF energy densities will overlap those of nuclear weapons; the shaded area represents the region of high energy density. Note, however, that in measures of total energy, NIF energy regimes are well below the weapons test regime.**

and go to the detector. The measured absorption of this well-characterized and well-controlled x-ray source provides insight into the characteristics of the target material. The timing of the heating beams and backlighter beams can be independently controlled to probe the targets under a wide variety of conditions.

Although the experimental program at NIF evolves from techniques developed on Nova, NIF experiments will probe the qualitatively different regime of plasmas characterized by radiation dominance at high-energy densities. The three examples of laser-driven experiments described here figure prominently in weapons research on the NIF: opacity, equation-of-state, and hydrodynamic instability experiments. Each of these explores a different set of fundamental phenomena characteristic of the extreme conditions within a nuclear weapon. In all three experiments, we can analyze how far the 1.8-megajoule drive of NIF can push the energy density.

**Opacity Experiments**

Loosely defined, opacity is the degree to which a medium absorbs radiation of a given wavelength. Knowledge of the opacity of a medium is crucial to understanding how the medium absorbs energy and transmits it from one place to another. This knowledge is important in nuclear weapons, where we care specifically about opacities at x-ray wavelengths, because this is the manner in which much of the energy in a weapon is transported.

If we are analyzing radiant energy transfer in a medium that is locally in thermodynamic equilibrium (LTE), we need know only an appropriate average of the mean distances that a photon can travel before it is absorbed—that is, its Rosseland mean free path between emission and absorption. (To analyze radiant energy transfer in a medium that is not in thermal equilibrium, we would have to retain detailed transmission information for every wavelength.) To achieve LTE for opacity experiments, we use the indirect method described above, creating a bath of x rays inside of a hohlraum. We thus make a diagnosable plasma in equilibrium and then determine its x-ray transmission at the appropriate wavelength.

To make a good plasma, the sample must be carefully tamped so that it retains uniform density under heating while hydrodynamically expanding to the desired density during measurement. The measurement is performed by passing backlighter x rays through the hohlraum to probe the tamped target. The target may have sections of different thickness so that, when analyzing the film image, we can separate the actual sample opacity from the absorption of radiation by other parts of the experiment. Figure 3 shows a typical transmission experiment in local thermal equilibrium.[2] Generally, as the atomic number is increased, we need to either increase the temperature of the tamped target, or lower its density, or both, in order to strip off enough electrons from the atoms in the target to ionize the plasmas to the desired level. Reaching such ionizations in the materials relevant to weapons requires a much more powerful laser than Nova, as Figure 4 shows.

Opacity research on the NIF will be conducted to evaluate new methods for predicting opacities. Such predictions are difficult, because there are many transitions and competing ionization stages that can contribute to the opacity of a given element. The electrons in atoms are arranged in shell structures of increasing complexity (from innermost outward), and the shells are conventionally labeled K, L, M, N, etc. M-shell-dominated opacities occur when an atom has been stripped of enough electrons to open the M shell. Complicated configurations of

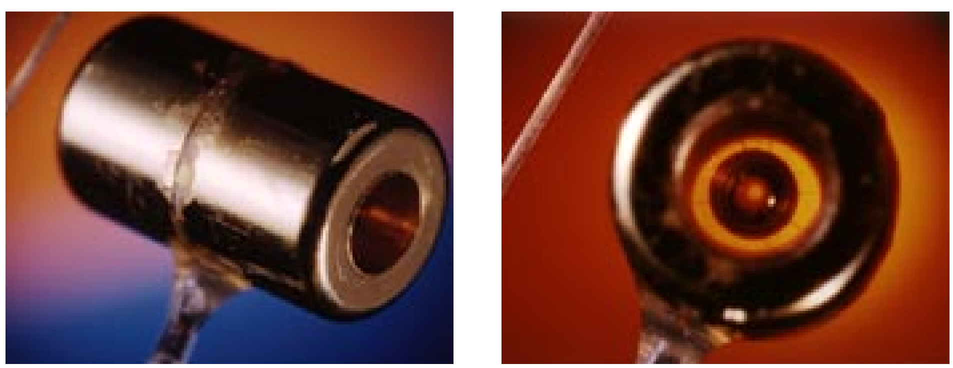


**Figure 2.** Two views of a typical Nova hohlraum shown next to a human hair. The end-on view shows a target within the hohlraum. Hohlraums for NIF will have linear dimensions about five times greater than those shown.

this sort play an important role in determining opacity; for example, the M-band opacity of materials involves computing features of $10^8$ ionic configurations. Clearly this is impossible in any direct way; present ideas necessarily involve predicting key features with approximate statistical methods.[3] Experiments are crucial in checking that these models and predictions are correct.

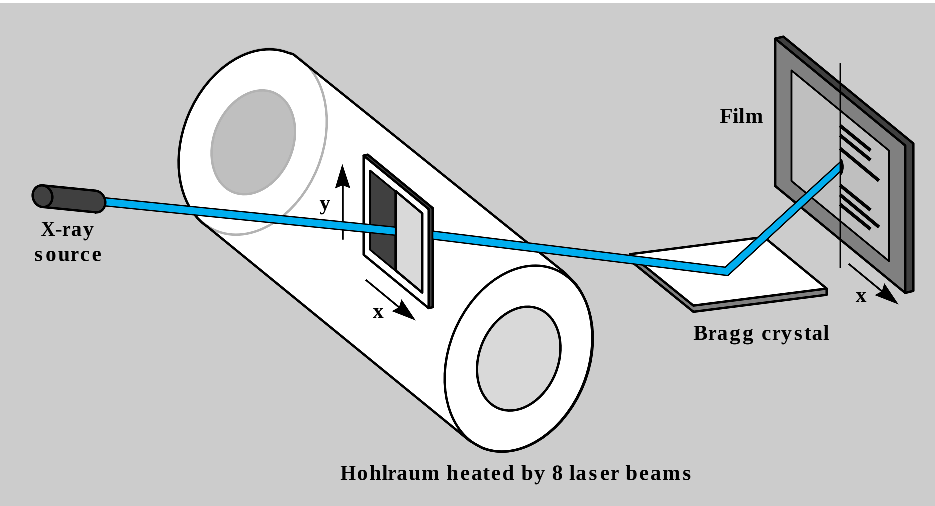
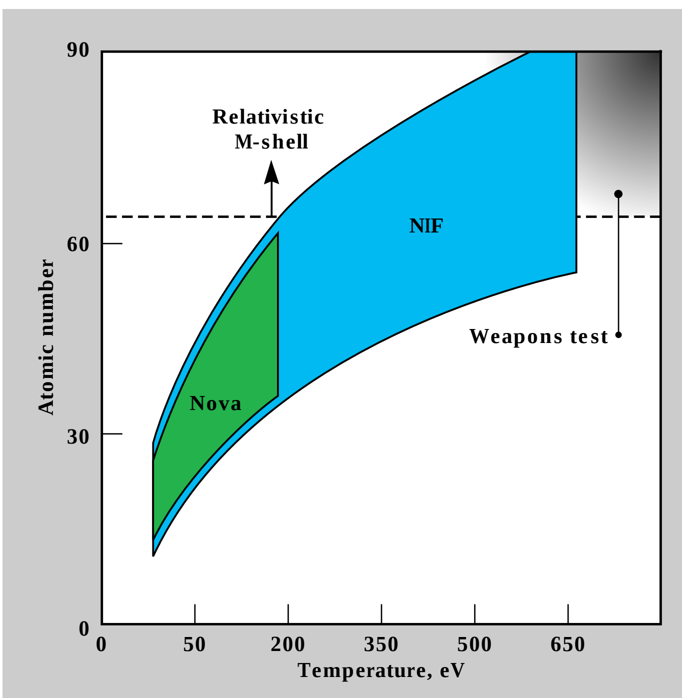



**Figure 3.** Schematic of a setup for absorption opacity experiments. The tamped target has two thicknesses. Laser beams entering the hohlraum generate an x-ray bath to heat the target. Backlighter x rays have significantly higher energies than the driver x rays.

**Figure 4.** Comparison of opacity regimes achievable on Nova and NIF and in weapons tests.

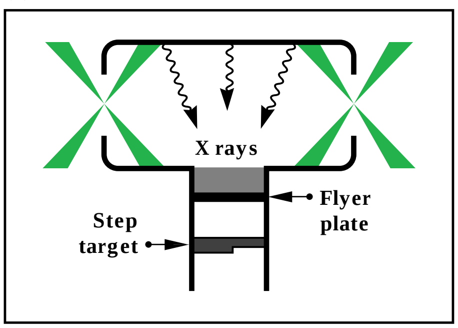



## Equation-of-State Experiments

Understanding the physics of nuclear weapons requires that we answer the practical question of how much pressure is developed in a given material when a given amount of energy has been added. That is, we must determine the material's equation of state: the thermodynamic relationship between the energy content of a given mass of the material and its pressure, temperature, and volume.

Figure 5a shows a setup for a shock breakout experiment—an experiment for determining the thermodynamic states created by the passage of a single shock wave through the subject material. By striking a material at standard temperature and pressure with single shocks of different strengths, we obtain a set of states that lie on the principal Hugoniot. Hugoniots not only describe how materials behave when shocked; they also serve as baselines for models of much of the thermodynamic space covered by the full equation of state. Hugoniot experiments present a rare case in which thermodynamic quantities such as pressure can be determined from the measurement of material velocities alone.

In a shock breakout experiment,[4] lasers create an x-ray bath inside a hohlraum. The x rays heat an absorbing material that ablates, or rockets off, and sends a shock wave into a flyer plate. The flyer plate then hits a target that has two precisely measured thicknesses or "steps." The stepped target is observed end on by diagnostics that record the shock breakout. By measuring the difference in the timing of the shock breakout from the two sides of the step (Figure 5b), we can determine the speed at which the shock passed through the stepped material. However, shock breakout experiments are difficult to interpret. For example, we must determine whether the shock was planar: Did it strike the surface of the stepped plate with uniform force, or did the flyer plate undergo "preheat" and disassemble before it shocked the step? Like opacity studies, equation-of-state studies of these microscopic quantities are not only crucial to understanding the effects of high-energy densities in weapons, but they are crucial to understanding laser-based experiments themselves. Nova allowed us to study equations of state in the multimegabar pressure regions, but scaling equation-of-state experiments to pressures in the important gigabar region require a more powerful laser such as the NIF. This comparison is detailed in Figure 6.



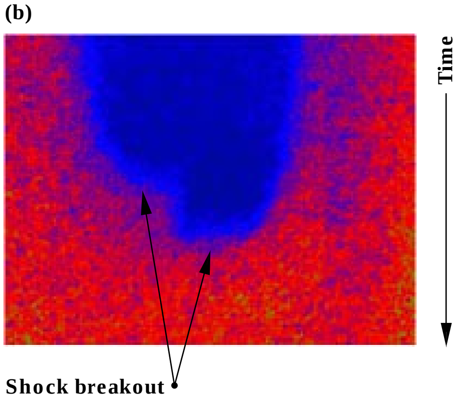




**Figure 5.** (a) Schematic of an x-ray-driven shock breakout experiment in colliding foils (the flyer plate and the step target are gold foil); (b) shows the breakout timing difference between the two sides of the step, as captured on film.

### Hydrodynamic Instability Experiments

The third experimental example uses indirect drive to create hydrodynamically unstable flows at high compressions and Reynolds numbers. Unstable flows in highly compressed materials are ubiquitous in weapon physics. We typically must determine the thickness of the mixing layer between two materials caused by the passage of a strong shock wave. Much research on turbulent flows relies on the assumption that the flow is incompressible (like water in an ocean). However, here we are interested in the situation where considerable compression and ionization can occur at the same time as turbulent, mixing motion.

Figure 7 shows the experimental setup for studying the instability growth at an interface caused by the passage of a controlled, planar shock. As before, the lasers heat the hohlraum to create the x-ray heat bath that drives the experimental package. Here, the x rays ablate a carefully designed sleeve that drives a shock into the instability experiment. Another laser beam makes an x-ray backlighter that allows us to "photograph" the growing instability. We must carefully check the equation of state of the subject materials, the planarity of the shocks, etc., before we can compare the experiment with a detailed simulation. Figure 8 shows a comparison between a preliminary instability experiment done on Nova and an arbitrary Lagrange-Eulerian hydrodynamics calculation of the same setup done to test the ability of the code to probe large-scale sliding motions and deformations.

The program of work in instability research involves the study of shocked mixing layer growth, and the evolution of compressible turbulence from the small-amplitude, linear

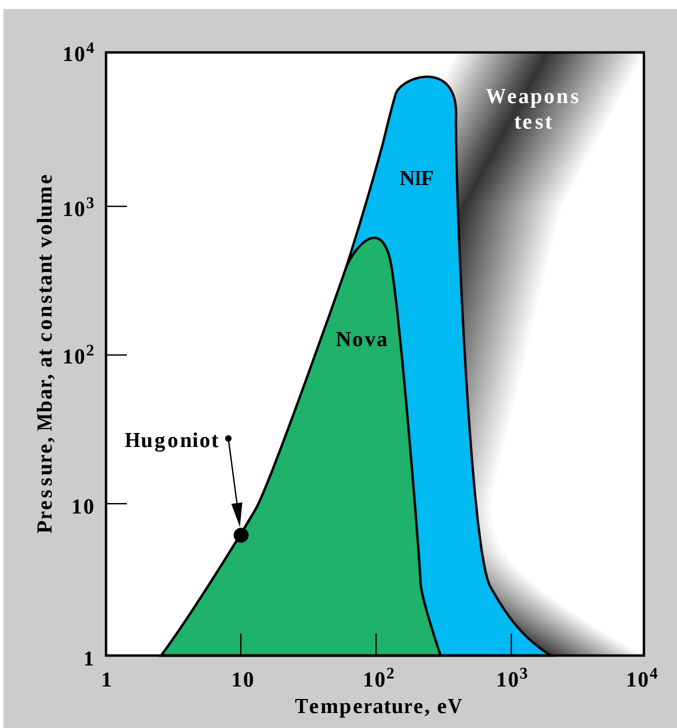



**Figure 6.** Comparison of equation-of-state regimes in flyer-plate experiments achievable on Nova and NIF; also roughly indicated is the weapons-test regime.

growth regime (which is pertinent to ICF implosions) to the full nonlinear evolution of turbulence. In the case of the mixing layers, there are suggestions for universal rules that control the width of such mixing layers as a function of time.[5] It would be of great importance to weapons designers to pin down these rules.

To explore the full evolution to turbulence from the simpler linear growth to the highly compressed turbulent regime, the experiments naturally scale to a higher-energy laser, as Figure 9 shows.[1]

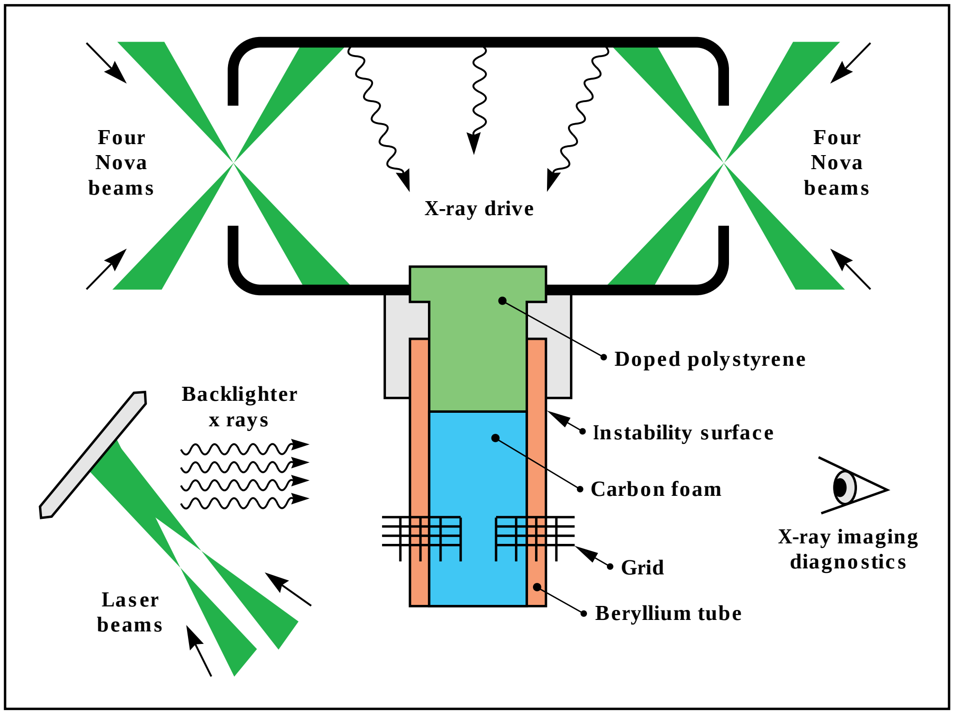



**Figure 7.** Schematic of a shock-driven hydrodynamic instability experiment. Changes in the transmission profile of the backlighter x rays reaching the diagnostics allow the mixing at the shocked interface to be measured.

## Other Weapons Experimental Realms

The three types of experiments just described are among the most fundamental that will be performed on NIF—fundamental in the sense of probing phenomena that are virtually irreducible. Several areas of investigation are more integrative, probing phenomena arising from combinations or interactions of several different processes. These areas, described below, will also receive intensive investigation on NIF. These investigations and those already enumerated will contribute to further refinement of our weapons codes.

**Radiation Transport.** We do not understand nuclear weapon processes well enough to calculate precisely the transfer of energy within a weapon.[6] This transfer is crucial, since inadequate energy coupling can degrade yield or cause failure. In the era of nuclear testing, this incomplete

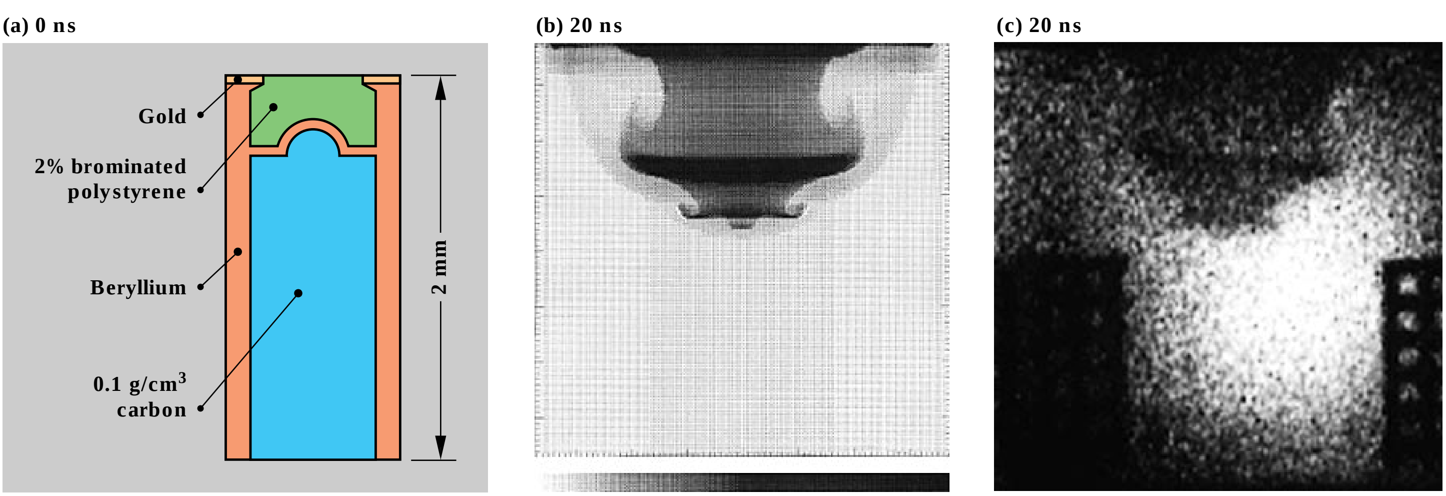



**Figure 8.** Calculated development of an axial jet compared with experimental data. (a) The experimental setup in initial conditions (0 nanoseconds). Center and right are the event after 20 nanoseconds: (b) is the calculation of instability evolution by arbitrary Lagrange-Eulerian code; (c) shows the data from an instability experiment on Nova.

understanding was not a problem because the radiative energy transfer could be determined specifically.

**Weapon Output.** The output of a nuclear weapon includes neutrons, gamma rays, x rays, fission products, activated elements, and exploding debris as kinetic energy. The ability to calculate the total spectral output of a weapon is an ultimate measure of our understanding of weapon performance.

**Role of Ignition.** Ignition encompasses two distinct weapons physics issues: weapons physics measurements and maintenance of critical skills. Several broad areas appear uniquely accessible to an ignition capsule:

- The possible use to study onset of DT ignition in the presence of impurities, which can occur from a mix of intentional contaminants placed in the gas. The NIF will provide the only place where DT burn will be studied in detail.
- The generation of x rays from the capsules. This will challenge our ability to model and understand burn, energy balance, and transport processes in a highly transient system having large gradients.
- The NIF capsules will also provide an intense source of 14-MeV neutrons. These neutrons could be used to heat material instantaneously to temperatures more than 50 eV without changing the material's volume. This unique capability may prove useful for other weapons physics studies such as equation-of-state experiments.

Designing NIF fuel capsules to tailor output and explore efficient operation is a challenge to designers, computational physicists, and engineers. Such modeling will challenge our understanding of many fundamental processes associated with weapon design and will help keep us intelligent in this critical technology.

**Non-LTE Physics and X-Ray Lasers.** The NIF will allow us to address important physics issues in situations in which plasmas are not in thermodynamic equilibrium (called nonlocal thermodynamic equilibrium, or non-LTE, physics). Understanding non-LTE effects plays an important role in determining x-ray outputs and in developing temperature, ionization balance, and kinetics diagnostics. It is also essential in the development of laser-driven x-ray lasers. In the specific area of x-ray lasers, NIF will allow us to explore x-ray laser pumping schemes with various materials and conditions.

An important benefit of the x-ray laser research is its use as an imaging system for ICF, weapons physics, and biology experiments. High brightness, narrow bandwidth, small source size, and short pulse duration give the x-ray laser many advantages over conventional x-ray illumination sources.[7]

Future imaging applications will include the study of laser-driven mass ablation on the interior walls of hohlraums, equation of state, and perhaps the ICF implosions themselves. As the NIF program for high-energy-density physics evolves, we expect these results to influence the development of further advanced diagnostics.

**Code Development.** To a large extent, our weapons computer codes embody the cumulative knowledge of weapons design. NIF data will help to improve and refine these codes to enable more accurate modeling of results from previous weapons tests and from weapons physics experiments past and future. Code development for ICF research has focused on the need to calculate many coupled physical processes in nonequilibrium conditions and to simulate all resulting experimental diagnostics within a single computational model. The future need for higher accuracy and increased engineering detail will require better numerical methods, three-dimensional simulations, and massively parallel computers. These growing ICF code capabilities will be very important to weapons researchers for

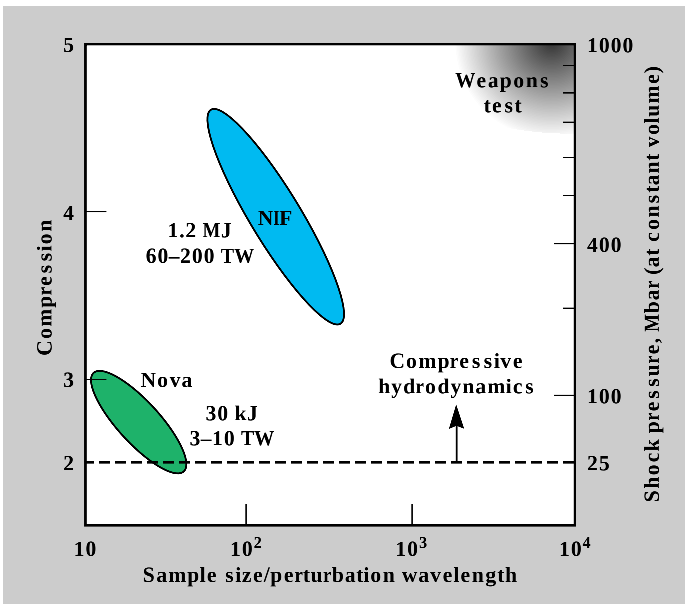



**Figure 9.** Whereas the moderate compressions on Nova allow us to follow the transition from linear instability to weak turbulence, the high compressions and larger scale volumes on NIF allow us to follow this all the way to turbulent mix.

understanding the results of NIF weapons physics experiments.

## Summary

Underground nuclear tests played an important role in advancing knowledge of the physics of nuclear weapons. This knowledge led to progressively safer and more effective performance and to retrofits for older designs that improved their safety as well. Results from tests also enabled us to build and refine our weapons computer codes. The unilateral moratorium that the United States imposed on underground nuclear testing is likely to be followed by a Comprehensive Test-Ban Treaty. The United States must therefore have an alternative means of safely and securely maintaining its stockpile of nuclear weapons and ensuring their reliability. Stockpile stewardship is one of the functions to which the National Ignition Facility will contribute by virtue of experimental work in the physics of nuclear weapons.

The total energy output from thermonuclear ignition on NIF will be an extremely tiny fraction of the energy from even the smallest nuclear weapon—indeed it will be roughly equivalent to the output of a gallon of gasoline. Nevertheless, experiments will generate the same energy densities—energies per particle—that occur in nuclear weapons. This combination of low total energy with weapons-regime energy density will allow us to pursue, besides ignition experiments, many nonignition experiments. These will allow us to improve our understanding of materials and processes in extreme conditions by isolating various fundamental physics processes and phenomena for separate investigation. Such studies will include opacity to radiation, equations of state, and hydrodynamic instability. In addition to these, we will study processes in which two or more such phenomena come into play, such as in radiation transport and in ignition itself.

Weapons physics research on NIF offers a considerable benefit to stockpile stewardship not only in enabling us to keep abreast of issues associated with an aging stockpile, but also in offering a major resource for attracting and training the next generation of scientists with nuclear stockpile expertise. According to the recent JASON report on stockpile stewardship, the NIF "will promote the goal of sustaining a high-quality group of scientists with expertise related to the nuclear weapons program."[8]

**Key Words:** inertial confinement fusion; National Ignition Facility; Stockpile Stewardship Program.

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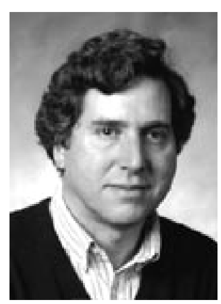

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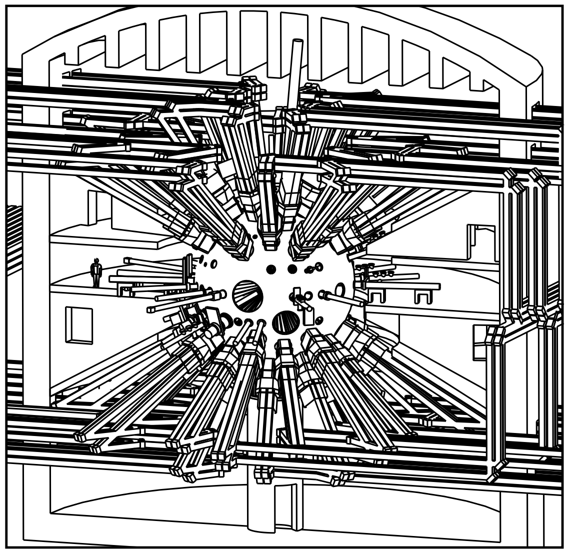
# The Role of NIF in Developing Inertial Fusion Energy



*The National Ignition Facility will demonstrate fusion ignition, which is central to proving the feasibility of inertial fusion energy. It will also help us determine the full potential of this alternate energy source.*

AMERICA'S dependence on imported oil currently accounts for a trade deficit of $60 billion per year. As time passes, the world demand for energy will continue to grow, in part for demographic reasons, such as the rapidly increasing energy use per capita in developing Asian and Latin American countries together with the expected doubling of the world's population over the next 50 years. Our deficit and world energy demand will also grow for environmental reasons, particularly in the United States, which will need a substantial new source of energy to power zero-emission transportation and reduce urban air pollution, to charge batteries in electric cars, or to produce clean-burning hydrogen fuel by water electrolysis. Clearly, an alternative energy source is needed.

At present, there are only three known inexhaustible primary energy sources for the future: the fission breeder reactor, solar energy, and fusion. All are superior to coal or oil-based power plants because they are environmentally cleaner and ecologically safer. They will release little or no radioactivity per unit of power, as do coal mining and burning in the form of radon, uranium, and thorium,[1] and they will emit none of the gases (carbon dioxide and nitrogen dioxide) that contribute to greenhouse effects. Fusion, however, offers certain advantages over fission and solar energy. Unlike solar energy, which is only dependable in the limited desert regions of the world, some fusion fuels can be extracted from seawater, making them available to all countries of the world. Fusion power plants, if they can be developed economically, will also have many advantages over fission. The radiation hazard presented by fusion power plants can potentially be thousands of times smaller than that of fission power plants, with proper choice of materials.

## Two Approaches to Fusion

Fusion combines nuclei of light elements into helium to release energy and is the same process that powers the sun. As noted, the fuel for fusion (deuterium and lithium, which can capture a neutron to regenerate tritium) can be extracted from seawater. The most likely fuel for any approach to fusion energy is DT (either liquid, gas, or a combination as in inertial fusion energy targets), which is a mixture of deuterium and tritium isotopes of hydrogen. This DT must be heated until it is hotter than the interior of the sun, but it fuses at the lowest temperature of any fusion fuel.

To explore the feasibility of economical fusion power plants, the Department of Energy is currently developing two primary approaches to fusion energy—magnetic fusion energy and inertial fusion energy (IFE). Both approaches use DT fuel and offer the potential advantages described above, but they must be developed more fully before economical fusion energy can be assured. Because the two approaches use different physics and present different technological challenges, the *National Energy Policy Act of 1992*[2] calls for both to be developed to the demonstration (DEMO) stage.

Magnetic fusion ignition is the goal of the proposed International Thermonuclear Experimental Reactor, which uses strong superconducting magnets to confine a low-density DT plasma inside a large, high-vacuum, toroidally-shaped vacuum chamber.[3] The IFE approach to fusion, in contrast, is one of the goals of the National Ignition Facility (NIF), the subject of this article. This approach uses powerful lasers or ion beams (drivers) to demonstrate fusion ignition and energy gain in the laboratory by imploding and igniting small, spherical DT fuel capsules (targets) to release fusion energy in a series of pulses (see box on p. 38). In its quest to accomplish this goal, the NIF supports a primary national security mission for science-based stockpile stewardship (see preceding article) and secondary missions supporting energy and basic science.

## The IFE Power Plant

Figure 1 is a conceptual view of a generic IFE power plant, showing its four major parts—the driver, target factory, fusion chamber, and steam-turbine generator (balance of plant). This figure demonstrates some of the principal advantages of IFE as an energy source:

- The driver and target factory are separated from the fusion chamber to avoid radiation and shock damage to the most complex plant equipment. The separation between the driver and fusion chamber also allows a single driver to drive multiple fusion chambers, thus permitting flexibility in the required chamber pulse rate and lifetime and allowing for the staged deployment of several fusion chambers to achieve low-cost electricity.[4]
- Progress in inertial fusion experiments on the Nova laser facility at LLNL allows the most important target physics affecting target gain to be modeled successfully by computer codes such as LASNEX. When these computer models are better confirmed by target-ignition tests in the NIF, they can be used to design targets for future IFE power plants.
- IFE fusion chambers do not require a hard vacuum; therefore, a wider range of materials can be used to achieve very low activation and radioactive waste. IFE chamber designs that protect the structural walls with thick, renewable fluid flows are also possible, which will eliminate the need to replace the chamber's internal structural components periodically.[5,6]
- The cost of developing IFE can be diluted by sharing NIF for defense and energy missions.

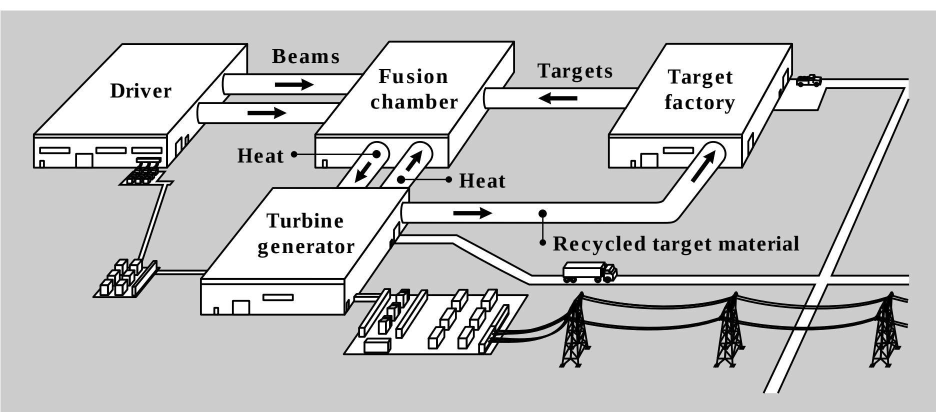



**Figure 1.** **Conceptual view of a four-part IFE power plant, showing the driver (either laser or ion particle beams), the target factory, the fusion chamber, and the turbine generator that produces electricity.**

## How the NIF Can Help Develop IFE

In 1990, the Fusion Policy Advisory Committee[7] recommended that inertial fusion ignition be demonstrated in the NIF as a key prerequisite to IFE. In addition to ignition, IFE needs development in three major areas of technology:

- High-gain, injectable, mass-produced, low-cost targets.
- An efficient high-pulse-rate driver.
- A suitable, long-lasting fusion chamber.

A major facility following the NIF, to be called an Engineering Test Facility

(ETF), is planned to test the feasibility of these three areas of technology integrated together. The ETF will explore and develop the high pulse rate (several pulses per second) and overall system efficiency needed for economical IFE power production.

### Filling Technological Needs

**Targets.** The targets for IFE must be capable of high energy gain. Energy gain is achieved when the fusion energy released from a reaction exceeds the energy that was put into the target by a laser or ion-beam driver. For high gain, the energy released from the target should be more than 50 to 100 times greater than the driver energy. Tests of inertial fusion target physics and ignition in the NIF will allow us to predict confidently the performance of several candidate IFE target designs.

For IFE targets to produce electricity at competitive rates (less than 5 cents per kilowatt-hour), they must be mass-producible at a cost of less than 30 cents each. This means new target-fabrication techniques must be researched and developed. In addition, we will have to develop and test methods of target injection and tracking for driver–target engagements at pulse rates of 5 to10 Hz. The NIF can test the performance of candidate mass-produced IFE targets and, at least for a limited number of pulses in a short burst, the associated target-injection methods.

The option of using direct-drive in addition to indirect-drive targets (see the box on pp. 38-39) is under consideration for the NIF. If direct-drive implosion experiments on the Omega Upgrade (an upgrade of the Omega glass laser to 60 beams) at the University of Rochester's Laboratory of Laser Energetics are successful, this option will be exercised, and both direct- and indirect-drive targets will be examined on the NIF. Figure 2

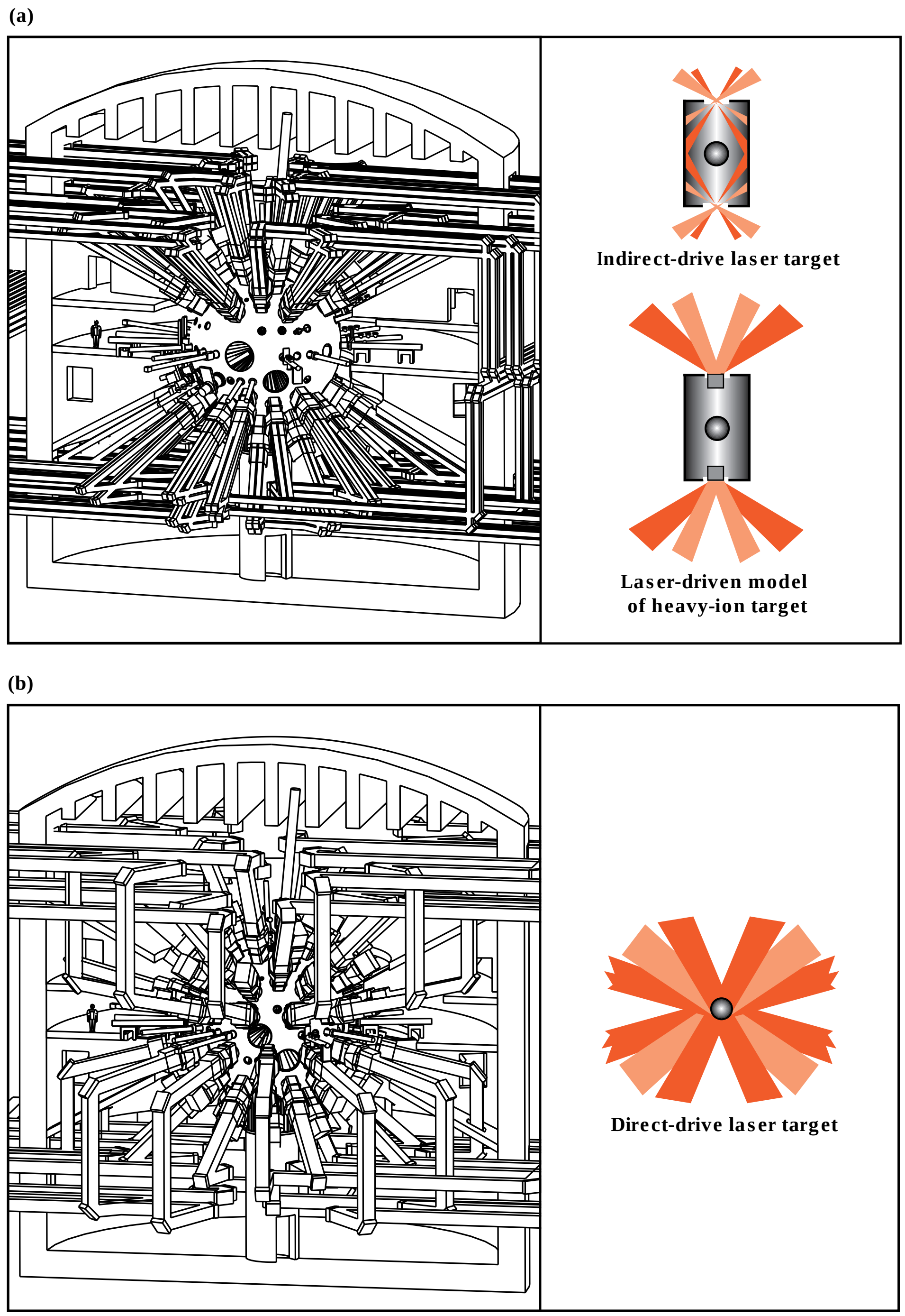



**Figure 2.** The NIF target area and beam-transport system (a) for indirect-drive experiments relevant to either laser or heavy-ion targets and (b) for direct-drive laser targets only. Note that the target area and beam-transport system in the baseline system (a) could be reconfigured to design (b) by the repositioning of 24 four-beam clusters, making direct-drive experiments possible.

shows the laser-beam configurations around the NIF fusion chamber that will be used to conduct indirect-drive (Figure 2a) and direct-drive experiments (Figure 2b). Figure 2 also shows examples of indirect- and direct-drive targets that can be tested in each configuration.

Figure 3 shows a heavy-ion-driven target for IFE (Figure 3a) compared with a modified laser-driven target (Figure 3b) that is designed to model more closely the IFE heavy-ion target. The latter (Figure 3b) illustrates how the NIF could use a laser to test the soft-x-ray transport and plasma dynamics inside a higher-fidelity hohlraum geometry similar to that in Figure 3a. Note that the capsule performance and implosion symmetry requirements for indirect-drive targets are independent of whether the x rays are generated with a laser or an ion-beam driver. We can also use the NIF for special laser-target experiments that simulate many aspects of heavy-ion targets.

**Drivers.** Although the key target-physics issues that NIF will resolve are largely independent of the type of driver used, it is essential in evaluating the potential of IFE to determine the minimum driver energy needed for ignition. Regardless of driver type, all IFE drivers for power plants need a similar combination of characteristics: high pulse-repetition rates (5 to 10 Hz) and high efficiency (i.e., driver output beam energy/electrical energy input to the driver greater than 10 to 20%, depending on target gain). In addition, they should be highly reliable and affordable when compared with nuclear generator plants.

The Energy Research branch of DOE is developing heavy-ion accelerators to meet the above requirements.[8] Heavy-ion drivers can be either straight linear accelerators (linacs) or circular (recirculating) beam accelerators like that shown in the box on p. 39. The Defense Programs branch of DOE, in contrast, is pursuing advanced solid-state lasers, krypton–fluoride lasers, and light-ion pulsed-power accelerators for defense applications that may, with improvements, lead to alternate IFE drivers. Diode-pumped solid-state lasers will be able to build on the laser technology being developed for the NIF.[9]

While other DOE research examines the direct-drive option and develops more efficient, high-repetition-rate IFE drivers (principally heavy-ion beam accelerators) for power plants, the NIF can be built and achieve its mission with current solid-state laser technology. Diode-pumped solid-state lasers (DPSSLs), which also build on NIF laser technology, may prove to be a backup to the heavy-ion accelerator. Using laser-diode arrays under development for industrial applications, DPSSL drivers may ultimately improve the efficiency, pulse rate, and cost of solid-state lasers enough for use as IFE drivers. Figure 4 shows a schematic DPSSL driver layout that, except for the diode pump arrays, has an architecture similar to that being developed for the NIF.

**Fusion chambers.** IFE needs fusion chambers where target fusion energy can be captured in suitable coolants for conversion into electricity. To allow high pulse rates, these chambers will have to be built so they can be cleared of target debris in fractions of a second. Further, they must be reliable enough to withstand the pulsed stresses of one billion shots (30 years of operation) without structural failure. They should also

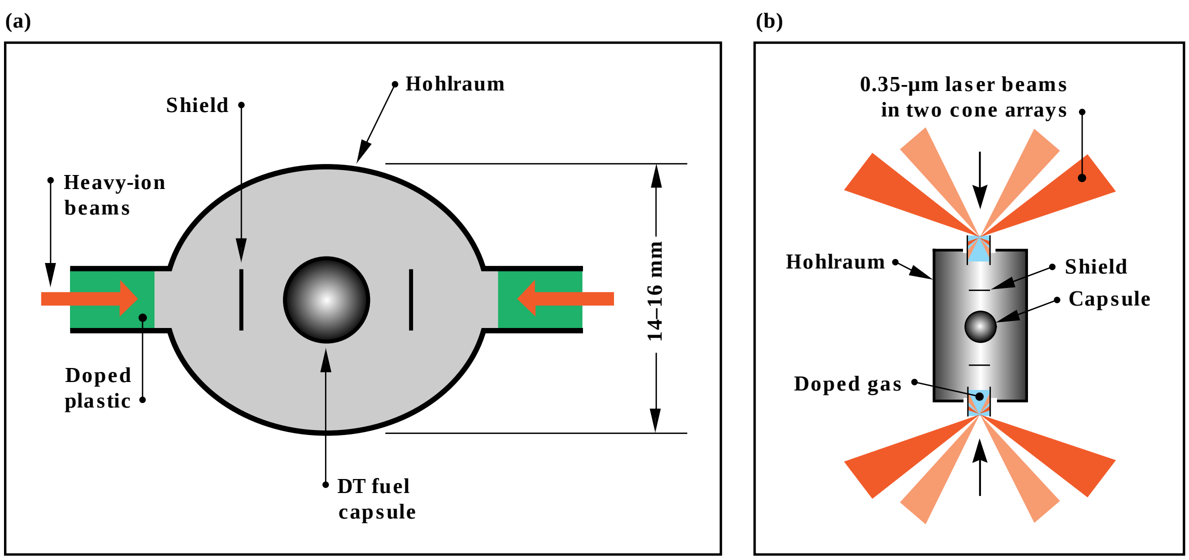



**Figure 3.** The NIF can test important heavy-ion physics issues, such as soft-x-ray transport and drive symmetry, hohlraum plasma dynamics, capsule-implosion hydrodynamics, and mix. Here the modified laser-driven target in (b) shows how the NIF could use a laser to test x-ray transport and plasma dynamics in a hohlraum geometry like that shown in (a).

use low-activation materials (such as molten salt coolants or carbon-composite materials) to minimize the generation of radioactive waste. Many IFE power plant studies have already found conceptual designs that meet these goals, but actual tests will be required. What we learn from the NIF fusion chamber can provide data to benchmark design codes for future IFE chamber designs.

**Other Needs.** In addition to fusion ignition, the NIF will provide important data on other key IFE power plant needs. These needs include wall protection from target debris and radiation damage, chamber clearing, rapid target injection, and precision tracking. The NIF will also be used to provide data that can benchmark and improve the predictive capability of various computer codes that will be needed to design future IFE power plants, to select among possible IFE technology options, and to improve our understanding of IFE target and chamber physics.

One predictive capability that can calculate and interpret material responses to neutron damage is a technique called molecular dynamic simulation (MDS).[10] MDS calculates responses at the atomic level by quantifying how a three-dimensional array of atoms responds to knock-on atoms that impinge on the matrix from a range of angles and with a range of energies as a result of an incident neutron flux. Potentially, MDS capabilities may include predicting, for a material, the number of vacancies and interstitials that will result from a neutron irradiation pulse, as well as the cluster fraction of defects, atomic mixing and solute precipitation, and phase transformations. Figure 5 shows how samples of materials exposed to the target neutron emission in a NIF shot can provide data that confirm the MDS model calculations.

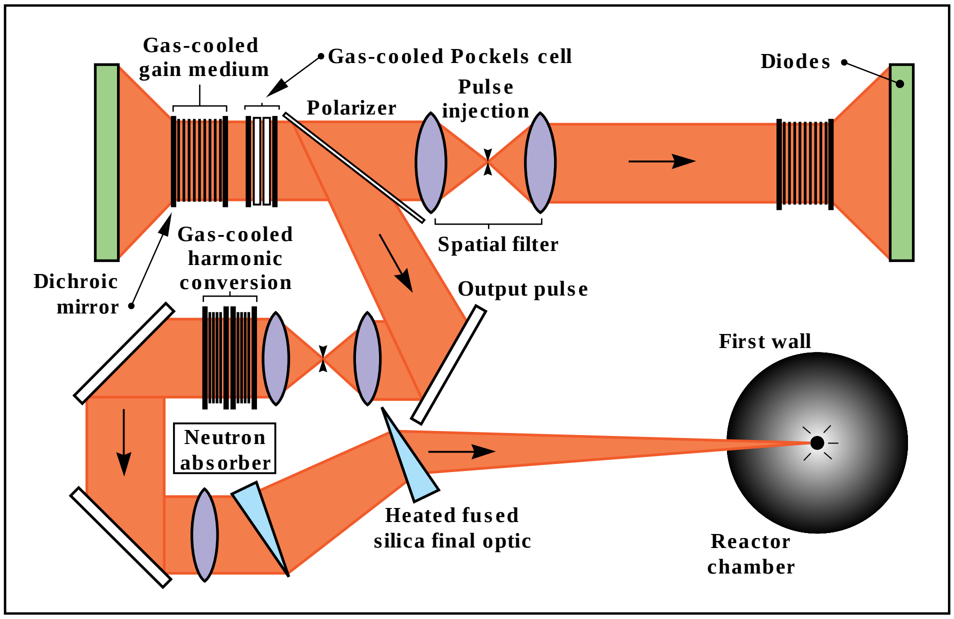



**Figure 4.** The diode-pumped, solid-state laser driver for IFE is similar in design to that being developed for the NIF. Although the NIF architecture will not include the diode pump arrays shown here, it will serve as an experience and technology base for the IFE driver. This figure shows a DPSSL IFE laser designed like the NIF in that it uses a multipass laser amplifier in which the laser beam is amplified by passing back and forth between the cavity mirrors four times before a Pockels cell optical switch sends the amplified beam out to the final optics and the target. However, the DPSSL uses light from arrays of efficient diode lasers to pump the amplifier from the ends rather than using light generated from flash lamps on the sides of the amplifier as in the present NIF design.

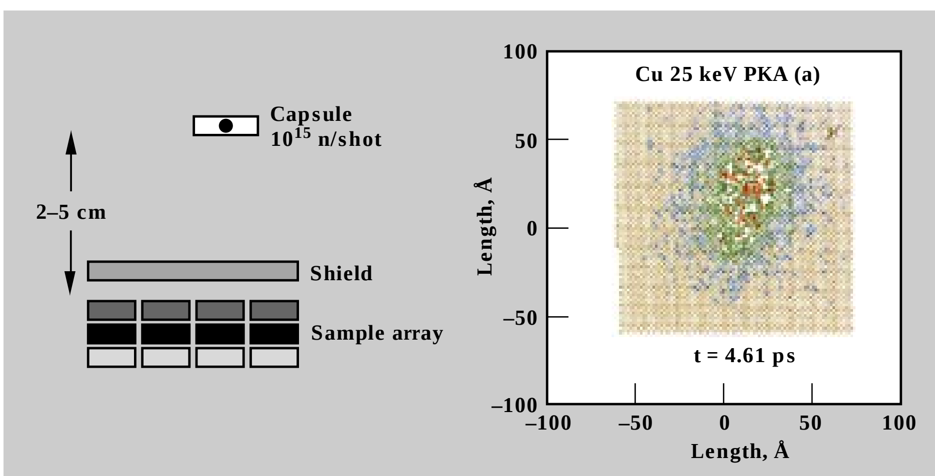



**Figure 5.** A molecular-dynamic simulation experiment on the NIF. Samples of 2- to 5-cm-width material placed within 20 cm of a NIF yield capsule (at left) will receive a significant exposure to 14-MeV neutrons ($10^{15}$ neutrons per shot per square centimeter of sample area). The tantalum shield will stop most x rays. Electron microscope images of the damage sites will be compared to MDS code predictions as shown at right. The figure shows a typical damage site in a copper sample due to primary knock-on copper atoms (25 keV primary knock-on atoms [PKA]) arising from collisions of fast neutrons with copper atoms in the sample.

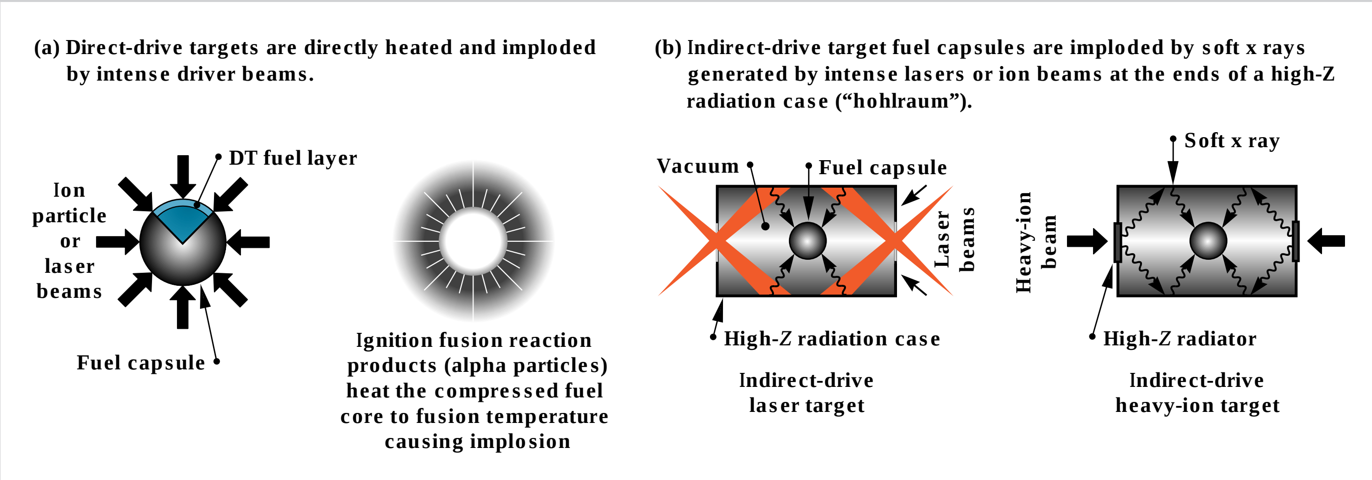
# Producing Inertial Fusion Energy

An inertial confinement fusion (ICF) capsule or target is a small, millimeter-sized, spherical capsule whose hollow interior contains a thin annular layer of liquid or solid DT fuel (a mixture of deuterium and tritium isotopes of hydrogen). The outer surface of the capsule is rapidly heated and ablated either directly by intense laser or ion particle beams (drivers), called direct drive (a below), or indirectly by absorption of soft x-rays in the outer capsule surface. These soft x-rays are generated by driver beams hitting a nearby metal surface, a process called indirect drive (b below).

The rocket effect caused by the ablated outer capsule material creates an inward pressure causing the capsule to implode in about 4 nanoseconds (a nanosecond is one billionth of a second). The implosion heats the DT fuel in the core of the capsule to a temperature of about 50 million degrees Celsius, sufficient to cause the innermost core of the DT fuel to undergo fusion. The fusion reaction products deposit energy in the capsule, further increasing the fuel temperature and the fusion reaction rate. Core fuel ignition occurs when the self-heating of the core DT fuel due to the fusion reaction product deposition becomes faster than the heating due to compression. The ignition of the core will then propagate the fusion burn into the compressed fuel layer around the core. This will result in the release of much more fusion energy than the energy required to compress and implode the core.

An inertial fusion power plant would typically fire a continuous series of targets at a pulse rate of 6 Hz. The series of fusion energy releases thus created in the form of fast reaction products (helium alpha particles and neutrons) would be absorbed as heat in the low-activation coolants (fusion chamber) that surround the targets. Once heated, the coolants would be transferred to heat exchangers for turbine generators that produce electricity. The inertial fusion power plant example shown below uses jets of molten salt, called Flibe, surrounding the targets inserted into the fusion chamber. The molten salt jets absorb the fusion energy pulses from each target while flowing from the top to the bottom. The molten salt is collected from the bottom of the chamber and circulated to steam generators (not shown) to produce steam for standard turbine generators. This particular power plant example uses a ring-shaped ion beam accelerator as a driver, but there are also laser driver possibilities.

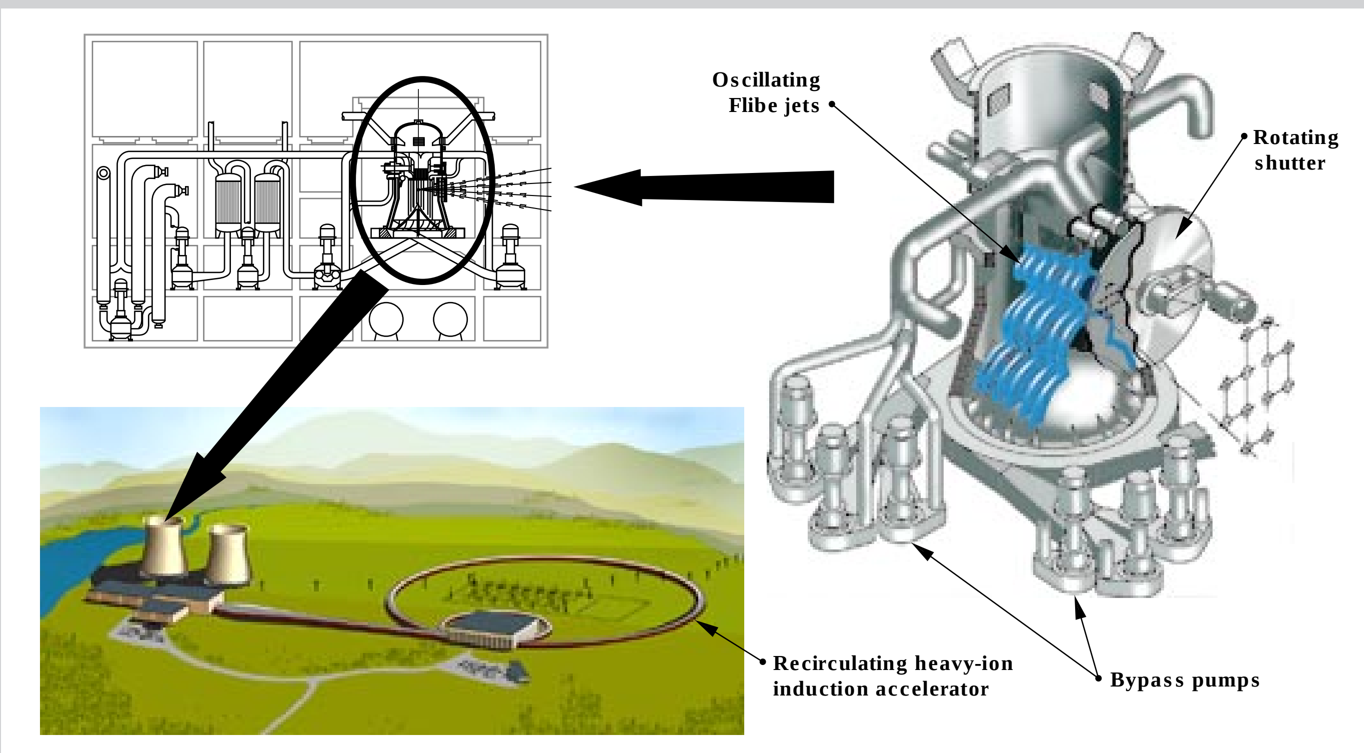
The minimum driver energy required to implode the capsule fast enough for ignition to occur is typically about a megajoule, the caloric equivalent of a large doughnut. Since this driver energy must be delivered in a few nanoseconds, however, a power of several hundred terawatts (1 terawatt = 1 million megawatts) will be needed. For reference, the entire electrical generating capacity of the United States is about one-half terawatt.



The rapid thermal motion of the deuterium and tritium nuclei will cause a significant fraction of them to collide and fuse into helium ash before the compressed fuel mass from the implosion has had time to rebound and expand. The reaction products will fly away with several hundred times more kinetic energy than the thermal energy of the deuterium–tritium ion pair before fusion occurred. If some inefficiency in coupling the driver laser or ion-beam energy into compressing and heating the capsule is taken into account, the ratio of fusion energy produced by the target to the driver beam energy input to the target—called the target gain—can range from 50 to 100 in a typical power plant. Once this fusion heat is converted into electricity, the average amount of electricity needed to energize the driver would be 5 to 10% of the total plant output.

Inertial fusion targets are of two basic types: direct drive and indirect drive, both of which will be tested by the NIF to determine the best target for inertial fusion energy. A direct-drive target consists of a spherical capsule driven directly by laser or ion beams. So that the capsule will implode symmetrically and achieve high gain, it must be illuminated uniformly, from all directions, by many driver beams. In indirect-drive targets, the fuel capsule is placed inside a thin-walled cylindrical container (hohlraum) made from a high-atomic-number material, such as lead. Here a smaller number of driver beams (with a total energy similar to that required for direct drive) are directed at the two ends of the hohlraum cylinder, where the driver beam energy is converted to soft x rays, which, in turn, lead to the compression of the fuel capsule. The hohlraum spreads the soft x rays uniformly around the capsule to achieve a symmetric implosion.

For its driver, the NIF will use a solid-state glass laser to deposit the externally directed energy. This laser will deliver 1.8 MJ of laser light energy (in pulses spaced several hours apart) to test the minimum energy required for target ignition and the scaling of target gain so that any type of target optimized for future power plants can be designed with confidence. DOE–Energy Research is developing heavy-ion beam accelerators as its leading candidate drivers for future IFE power plants, while DOE–Defense Programs is developing other driver technologies for ICF research, including advanced solid-state lasers, that could lead to alternative IFE drivers as well.



## Developing Fusion Power Technology

The NIF can also help develop fusion power technology (FPT), which includes the technologies needed to remove the heat of fusion and deliver it to the power plant. The primary functions of such components in IFE power plants are to convert energy, to produce and process tritium, and to provide radiation shielding. The dominant issues for FPT in IFE power plants concern component performance (both nuclear and material) so as to achieve economic competitiveness and to realize safety and environmental advantages. In this regard, NIF will provide valuable FPT information gained from the demonstrated performance and operation of the NIF facility itself, as well as from experiments designed specifically to test FPT issues. NIF's relevance to FPT has to do with both its prototypical size and configuration and its prototypical radiation-field (neutrons, x rays, and debris) spectra and intensity per shot. The most important limitation of NIF for FPT experiments is its low repetition rate (low neutron fluence), and its most important contributions to FPT development for IFE are related to:

- Fusion ignition.
- Design, construction, and operation of the NIF (integration of many prototypical IFE subsystems).
- Viability of first-wall protection schemes.
- Dose-rate effects on radiation damage in materials.
- Data on tritium burnup fractions in the target, tritium inventory and flow-rate parameters, and the achievable tritium breeding rate in samples.
- Neutronics data on radioactivity, nuclear heating, and radiation shielding.

The NIF will also be able to demonstrate the safe and environmentally benign operation that is important for IFE, including handling tritium safely and maintaining minimum inventories of low-activation materials. It is designed to keep radioactive inventories low enough to qualify as a low-hazard, non-nuclear facility according to current DOE and federal guidelines, thus setting the pattern for future IFE plants. Similar non-nuclear design goals will also be met for IFE power plants if the design selected for the fusion chamber is carefully followed and the low activation materials for it are used. The NIF will also demonstrate proper quality assurance in minimizing both

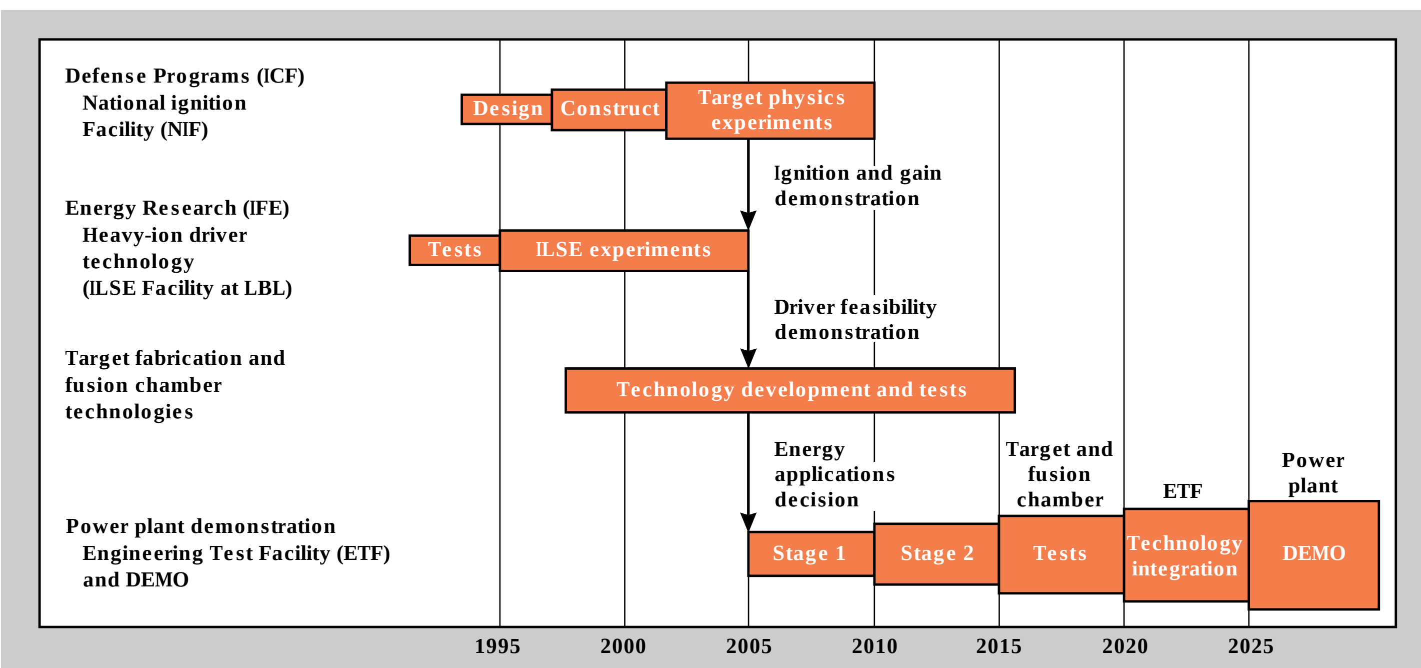



**Figure 6.** The timeline for IFE development includes ICF ignition and gain, IFE technologies, and the IFE power plant.

occupational and public exposures to radiation.

## An Integrated IFE Development Plan

To capitalize on the success of fusion ignition in the NIF, which is expected to occur around the year 2005, an Engineering Test Facility (ETF) will be needed. This facility will test the fusion power plant technologies called for in the 1990 Fusion Policy Advisory Committee[7] the 1992 *National Energy Policy Act of 1992*[2] plans. A decision to move forward with the ETF will also depend on the timely demonstration of a feasible, efficient, high-repetition IFE driver.

Figure 6 shows existing and proposed facilities in an integrated plan for IFE development. In addition to the NIF, they include:

- **The Induction Linac Systems Experiment (ILSE).** Plans call for this proposed heavy-ion accelerator test facility to be built at the Lawrence Berkeley Laboratory. Its mission will be to demonstrate the feasibility of a heavy-ion driver for IFE by testing critical, high-current, ion-beam-induction accelerator and focusing physics with properly scaled-down ion energy and mass. ILSE may be built in two stages for a total construction cost of about $46 million. The ILSE experiments should also be completed by the year 2005.
- **The ETF/Laboratory Microfusion Facility (ETF/LMF).** This multiuser facility for both defense experiments and IFE technology development will be able to produce target-fusion energy yields at full-power plant scale (200 to 400 MJ) and high pulse rates (5 to 10 Hz). As indicated, it will also drive multiple test fusion chambers for defense, IFE (ETF), basic science, and materials research, using a single driver to save costs. Its total construction cost is expected to be $2 billion in today's dollars, and its life-cycle costs to the year 2020 are expected to be $3 billion. Then a successful IFE chamber from previous tests will be upgraded to a higher average fusion power level. This upgrade, which is expected to provide a DEMO (net electric-power demonstration) by the year 2025, is shown as the last phase of the upgradable ETF/LMF facility.

Note in Figure 6 that the decision to initiate the ETF/LMF facility, including selecting an ETF/LMF driver, will be made after ignition is demonstrated in the NIF. An ETF with a single driver can be designed to test several types of fusion chambers at reduced power, greatly reducing the cost of IFE development through a demonstration power plant. This parallel approach to IFE development has already been endorsed by many review committees, including the National Academy of Sciences,[11] the Fusion Policy Advisory Committee,[7] the Fusion Energy Advisory Committee, and the Inertial Confinement Fusion Advisory Committee.[12] DOE–Defense Programs (using the NIF for fusion ignition and gain demonstration) and DOE–Energy Research will play complementary roles in driver development and other IFE technologies.

Chairman Robert Conn, in reporting the recommendations of the 1993 Fusion Energy Advisory Committee to then DOE Energy Research Director Will Happer, wrote: "We recognize the great opportunity for fusion development afforded the DOE by a modest heavy-ion driver program that leverages off the extensive target program being conducted by Defense Programs. Consequently, we urge the DOE to reexamine its many programs, both inside and outside of Energy Research, with the view to embark more realistically on a heavy-ion program. Such a program would have the ILSE as a centerpiece, and be done in coordination with the program to demonstrate ignition and gain by Defense Programs."[8]

## Summary

When the NIF demonstrates fusion ignition, which is central to proving the feasibility of IFE, it will tell us much about IFE target optimization and fabrication, provide important data on fusion-chamber phenomena and technologies, and demonstrate the safe and environmentally benign operation of an IFE power plant. In accomplishing these tasks, the NIF will also provide the basis for future decisions about IFE development programs and facilities such as the ETF. Furthermore, it will allow the U.S. to expand its expertise in inertial fusion and supporting industrial technology, as well as promote U.S. leadership in energy technologies, provide clean, viable alternatives to oil and other polluting fossil fuels, and reduce energy-related emissions of greenhouse gases.

**Key Words:** drivers—laser drivers, heavy-ion drivers; energy sources—fission breeder reactors, fossil fuels, inertial fusion energy, magnetic fusion energy, solar energy; fusion chambers; fusion power technology; International Thermonuclear Experiment; National Ignition Facility; targets—direct-drive targets, indirect-drive targets.

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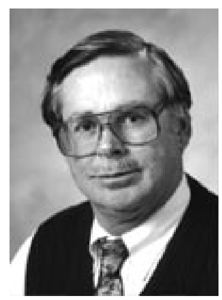

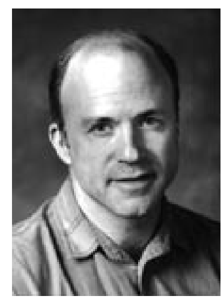

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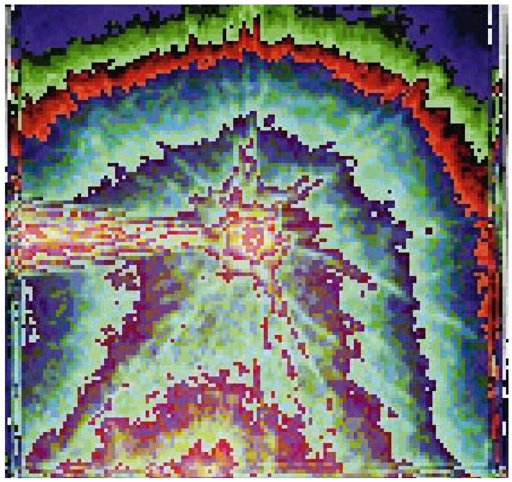
# Science on the NIF



***The National Ignition Facility will allow scientists to explore a previously inaccessible region of physical phenomena that could validate their current theories and experimental observations and provide a foundation for new knowledge of the physical world.***

LAST March, at the behest of the Department of Energy, a group of scientists from around the world convened at the University of California, Berkeley, to discuss potential scientific applications of the National Ignition Facility (NIF). The NIF is a 192-beam, neodymium glass laser that the Department of Energy will use to obtain information on high-energy-density matter, which is important for the generation of energy through inertial confinement fusion. This information will also be used to maintain the skills and information base necessary to manage the nation's nuclear stockpile, and most importantly from a scientific perspective, to pursue basic and applied research.

The objective of the gathering in Berkeley was to identify those areas of research in which the NIF and other high-energy lasers could be used to advance knowledge in the physical sciences and to define a tentative program of high-energy laser experiments. The scientists determined that the NIF as well as other high-energy lasers have effective application in areas relating to astrophysics, hydrodynamics, material properties, plasma physics, and radiation physics. Their determination was based on the wide range of experiments already being performed on high-energy lasers, the diverse interests of the scientific community, and the extraordinary range of physical conditions that would be achievable with the NIF—densities from one millionth the density of air to ten times the density of the solar core and temperatures that would be relevant to anything from a terrestrial lightning bolt (approximately $10^4$ K) to the core of a carbon-burning star ($10^9$ K).

In short, this versatile and powerful research tool would enable scientists in these fields to explore previously inaccessible regions of the physical parameter space that could validate current theories and experimental observations and provide a foundation for new knowledge. Following are the areas where the NIF is expected to make notable contributions to science and applied science.

## Astrophysics

To obtain information about stars and other astronomical bodies, the astrophysicist produces a sample plasma in the laboratory and studies its physical properties. For example, to determine a star's structure throughout the various stages of its lifetime—that is, its mass, heat, luminosity, and pulsational instabilities—the astrophysicist may require information on the radiative opacity of a plasma that mimics the outer stellar envelope and/or information on the equations of state (how density and temperature relate to the pressure or internal energy) of a plasma that resemble the dwarf star interior. Furthermore, to get a better idea of a star's structure during various stages of evolution, the astrophysicist may be interested in producing a stellar-like plasma to investigate its nuclear reaction rates. The key to success in all of these experiments is the ability to synthesize the very hot plasmas that characterize the stellar environment during stages of stellar evolution. The astrophysical community is interested in developing this potential with high-energy lasers, especially with the NIF.

## Equation of State

Under many circumstances, the equation of state of a stellar interior is simple: most of the gas is hydrogen and other light elements that have lost a good portion of their electrons. Unfortunately, the equation of state of the star's interior is not as simple when the star is in its later stages of evolution. Density is quite high, and the material becomes strongly coupled; that is, the ions interact strongly and no longer behave as free particles. This behavior is often accompanied by electron degeneracy. This leads to the tendency of the electrons to fill up certain energy states in a way that forces some of the electrons to be very energetic, thereby affecting the pressure and internal energy.

The theory of stellar evolution is affected by uncertainties in the equation of state in a few areas. For example, in white dwarfs—the "nuclear ashes," or compressed cores—of stars that have shed their hydrogen-containing outer layers and gone through most of their evolution, the pressure from degenerate electrons supports the material against gravity. Near the surface of the material, however, degenerate electrons lose their dominance. The ions then take over, setting the specific heat and establishing the rate at which the white dwarf will cool, a process that takes many millions of years.

## Radiative Opacity

The radiative opacity of the material in stellar interiors plays a key role in determining how stars evolve: what the maximum mass of a stable star is, how hot and how luminous the star is while it burns its hydrogen fuel, what pulsational instabilities may occur. Previous to recent experiments, astrophysicists were using a set of opacity calculations that predicted a very narrow range of surface temperatures for the hydrogen-burning phase of stellar evolution for all stars—in other words, all stars were very hot at this time despite their differences in mass. These calculations also tied pulsation instability to stellar luminosity and mass, which resulted in the wrong pulsation periods. The solution then was to correct the opacities used in the calculations.

In the last few years, a group of physicists at LLNL has been able to reduce the discrepancy by using a new set of opacity calculations. Although these are definitely closer to observation (Figure 1) than the

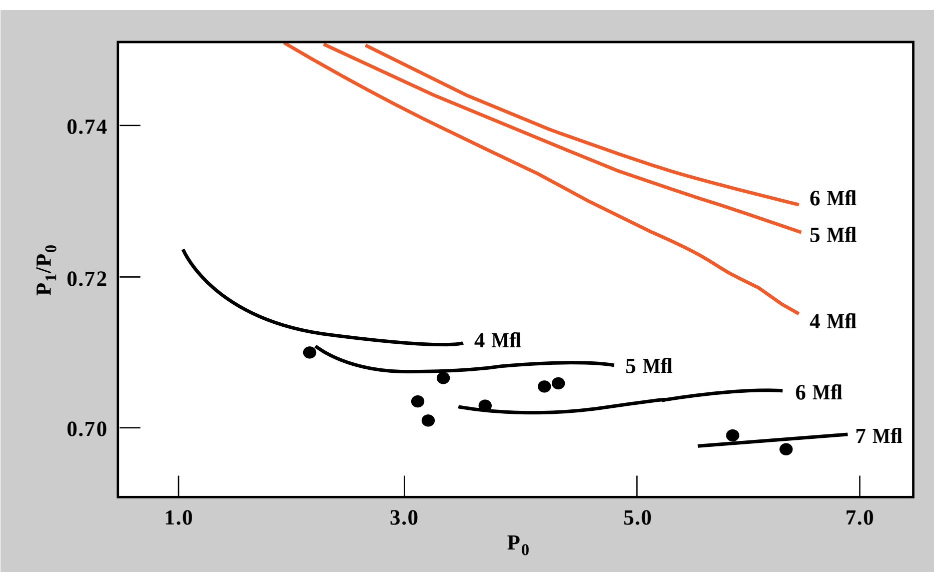



**Figure 1.** **The effects of opacity on pulsations of Cepheid stars. The stellar mass (Mfl) is predicted from the ratio of the first harmonic, $P_1$, to the fundamental, $P_0$. The black lines are the results based on the new opacity calculations; the red lines are the results based on the old opacity calculations; the dots are the observed ratios. The new calculations, which predict a much wider range of surface temperature for the hydrogen-burning phase of stellar evolution, put observation and theory in agreement. Experiments on the NIF will allow us to verify these effects and confirm our theoretical predictions.**

previous calculations, they still embody many approximations. Thus, to verify opacity at the relevant conditions, astrophysicists will need to conduct direct experiments. A high-energy facility like the NIF will allow them to do this.

### Thermonuclear Reaction Rates

Although astrophysicists have been studying nuclear reactions for decades, their experiments have rarely achieved the energies at which such reactions occur in stellar environments. With the NIF, they will be able to conduct experiments that achieve such energies. Figure 2 shows the temperature and density regimes attainable with the NIF and compares them to the conditions of a star as it progresses through each phase of evolutionary nuclear burning. The first regime, which extends up to about 14 keV, shows the temperatures and densities that may be reached in a laser-heated hohlraum or an imploding capsule without nuclear ignition and includes a star's hydrogen- and helium-burning phases. The second regime, which is between 9 and 60 keV, shows the conditions that might exist in a deuterium–tritium capsule after ignition and includes the temperatures and densities achieved up to a star's carbon-burning phase.

The nuclear cross sections depend on energy (temperature), and we are currently limited by conventional accelerator methods' inability to probe the relevant energy regimes of interest (see Figure 2). The NIF will allow us to measure the nuclear reaction rates at precisely the energies relevant to stellar interiors.

In a thermalized NIF capsule, where a temperature of 8 keV could be attained, the number of radioactive $^{13}$N nuclei, which would have a half-life of approximately 10 minutes, could be counted after the event, or scintillators could be positioned around the target to detect their pulse of 2-MeV gamma rays during the event. Because the events would be produced all at once in this type of experiment, the usual low signal-to-noise ratio would be avoided, making it easy to distinguish the reactions from ambient room background noise.

NIF experiments may further our understanding of nuclear reactions that explore the proton–proton chain of hydrogen-burning reactions in solar-type stars and also the carbon-nitrogen-oxygen cycle. As examples, three reactions of interest in astrophysics include the $^{12}$C(p,γ)$^{13}$N reaction, the $^{3}$He($^{3}$He,2p)$^{4}$He reaction, and the $^{3}$He($^{4}$He,γ)$^{7}$Be reaction. The first plays an important role in every star's carbon-nitrogen-oxygen cycle; the latter two form part of the proton–proton chain of hydrogen-burning reactions in solar-like stars.

## Hydrodynamics

Hydrodynamics is the study of fluid motion and the fluid's interaction with its boundaries. The NIF will allow us to further our understanding of the hydrodynamics of inertial confinement fusion and shock wave phenomena in the galaxy.

Because the NIF will be capable of depositing a large quantity of energy in a large amount of material over a long time and at high densities, it will be able to generate hydrodynamic flow conditions that are much more extreme than those generated by wind tunnels, shock tubes, or even

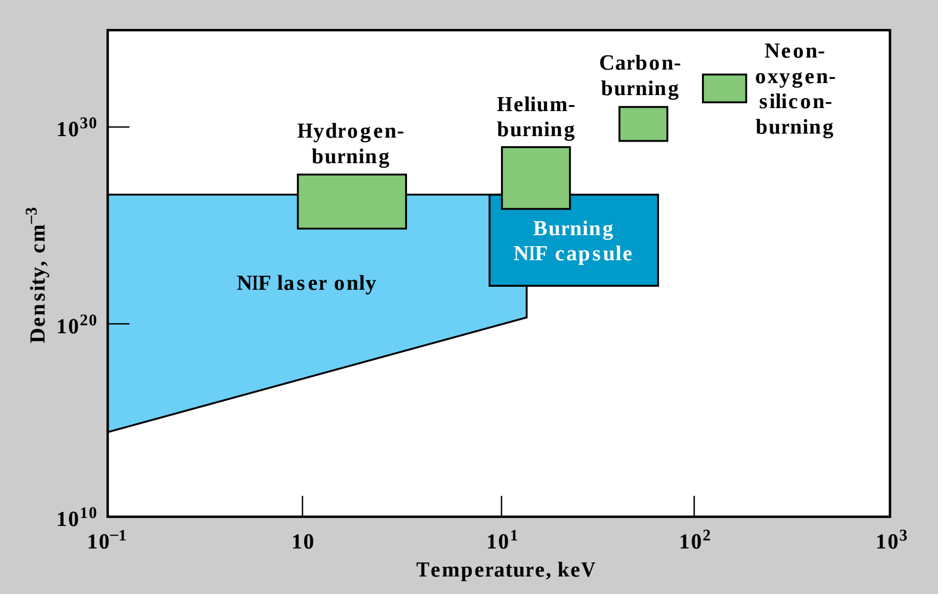



**Figure 2.** Temperature and density regimes attainable on the NIF overlap with the conditions of a star as it progresses through evolutionary nuclear burning. The first regime, which overlaps with a star's hydrogen- and helium-burning phases, could be reached in a laser-heated hohlraum or an imploding capsule without nuclear ignition. The second regime, which overlaps with the conditions achieved up to a star's carbon-burning phase, might exist in a deuterium–tritium capsule after ignition. Experiments conducted in these regimes could greatly enhance our knowledge of stellar evolution.

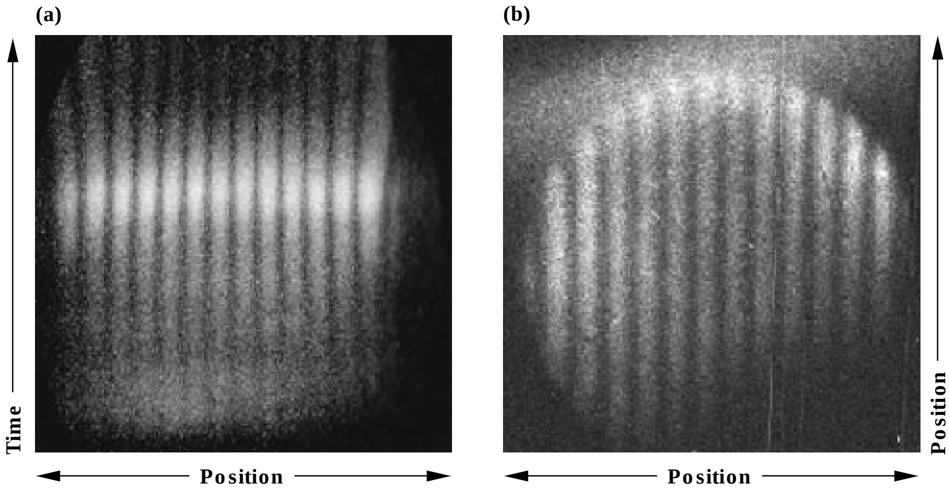
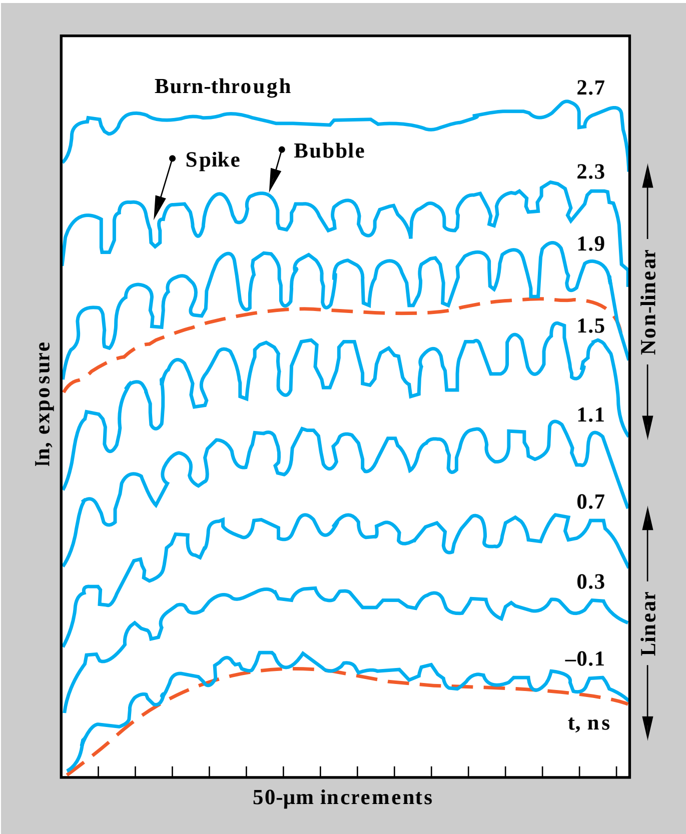



**Figure 3.** One- and two-dimensional views of the backlight absorbed by a foil with initial perturbation. The one-dimensional view (a) shows that the end of the bright spot occurs when the backlight ceases to radiate effectively. The face-on, two-dimensional view (b) shows little if any distortion of the foil.

**Figure 4.** Traces for an accelerated foil with an imposed perturbation. The curves are offset vertically to allow simple comparison. The dashed lines indicate the backlight intensity, which varies across the foil as a function of time.




high-energy lasers such as Nova. Thus, scientists will be able to investigate a number of flow problems under previously unattainable conditions. NIF experiments designed to study these problems—for example, the growth of perturbations at a fluid interface (unstable flow) and shock–shock boundary interactions (stable flow)—will lead to new understandings in fluid dynamics.

## Imposed Perturbations

To study the growth of an imposed perturbation under continuous acceleration, we shock planar foils of fluorosilicone by x-ray ablation. The foil trajectory is recorded by a radiographic streak camera so that we can check the bulk movement of the sample. The image's contrast in optical depth is then measured as a function of time. From this measurement, we deduce the evolution of the imposed perturbation.

Figure 3 shows two images of a foil from a perturbation experiment conducted on the Nova laser. The image on the left shows that foil has become increasingly bright; this is the result of thinning caused by the "bubble and spike" shape characteristic of the nonlinear regime. The image on the right, taken approximately 2.6 $\mu$s after the start of the drive for a duration of 100 ps, shows no transverse distortion of the foil.

We obtain quantitative data by taking intensity traces at different times transverse to the grooved structure, as shown in Figure 4. Note that the curves, which represent different times in the growth of the perturbation, are offset for ease of comparison. At early times, the growth is small and still sinusoidal, indicating that the instability is in the linear regime. Late in time, the growth is larger and distinctly nonsinusoidal, exhibiting the characteristic bubble-and-spike shape. The rapid flattening of the modulations in the top two curves results from the burn-through that occurs when the bubbles break out of the back side of the foil. At this point, the spikes are still being ablated away; however, they can no longer be replenished by matter flowing down from the bubbles.

These experiments extend from the single-mode example described here to multiple-mode experiments and to buried interfaces with imposed mode structures. The limiting case of a random set of perturbations at a buried interface requires a somewhat different technique.

## Impact Cratering

Many phenomena in impact cratering occur on temporal and spatial scales that are very large when compared to those of the impacting object; as a result, we can model the impact as a point source of high energy and momentum density. This modeling is usually done by depositing focused laser energy in small spheres of high-$Z$ (high-atomic-number) material or by generating prodigious shocks and post-shock pressures with flyer foils.

A study of concentrated impacts on surfaces shows that scaling laws apply to craters formed by impact and surface energy deposition. A proof-of-principle experiment designed to explore the effects of impact cratering on simulated soil (Figure 5) indicates that further research in this area would be of great interest. The ability of the laser to deposit large amounts of energy in a spot volume without residual gases—the by-product of the same experiment performed with high explosive—indicates its utility as a simulation source. On the NIF, the amount of energy deposited and the *in situ* diagnostic potential would make investigation of hydrodynamic response possible in real time.

## Material Properties

For the last several decades, scientists have been studying the physical properties of materials—e.g., their equations of state, opacity, and radiative transport—by conducting experiments with gas guns, high explosives, and high-pressure mechanical devices. Although these experiments have provided a wealth of precise data on a wide range of materials, they are limited because they do not provide information on material behavior at the extreme pressures and temperatures of scientific interest, i.e., pressures from 1 to 100 terapascals and temperatures up to a few hundred electron volts. Although a few laser-driven and shock-wave experiments have been carried out in this range of interest, the resulting data are quite imprecise and do not validate any of the theoretical models of material behavior.

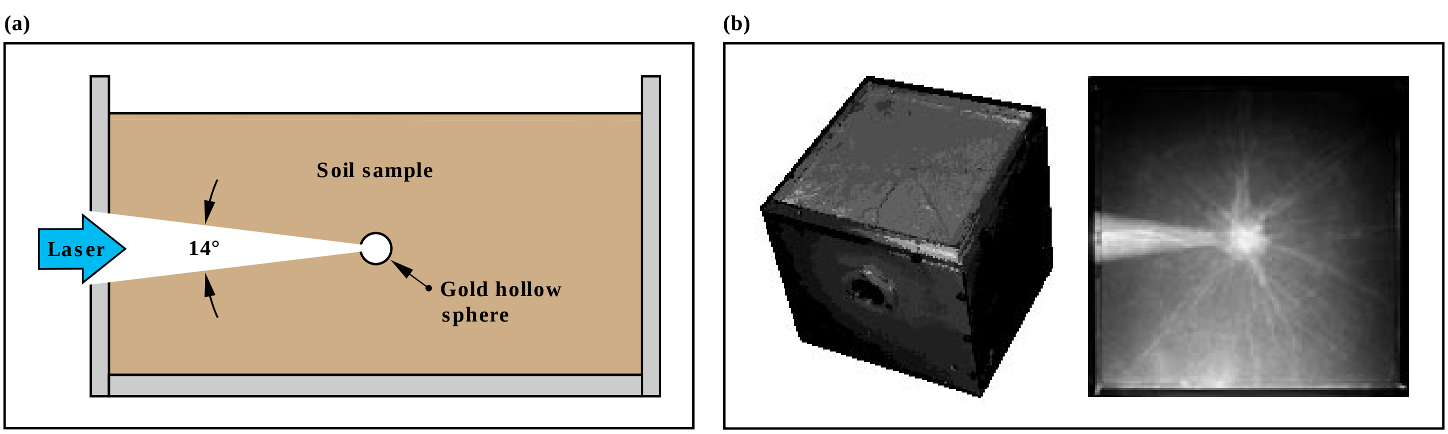



**Figure 5.** To explore the hydrodynamic response of a simulated soil to impact cratering, we deposited 4 kJ of laser energy into the 1.5-mm radius cavity of a 16 x 16 x 16-cm aluminum-plate cube filled with grout (a). The energy density provided by 4 kJ of laser energy in 1 ns was enough to vaporize a hollow gold target at the bottom of the 6-cm deep cavity and the surrounding grout. Less than 200 J of laser radiation escaped the target, as indicated by the top surface of the cube (b). Although this surface is crazed and slightly bowed, the cavity and the entry cone are clearly visible. There is also a profusion of radial cracks and a faint but definite indication of tangential (spherical) cracks. This diagnostic is an example of what we can learn from scaled experiments.

With the NIF, scientists will be able to investigate material behavior in this range and obtain the primary data needed to test their theoretical models. The experimental methods used to obtain these data include colliding foil experiments (for equation-of-state data) and high-resolution x-ray measurements (for radiative opacity data).

(a)

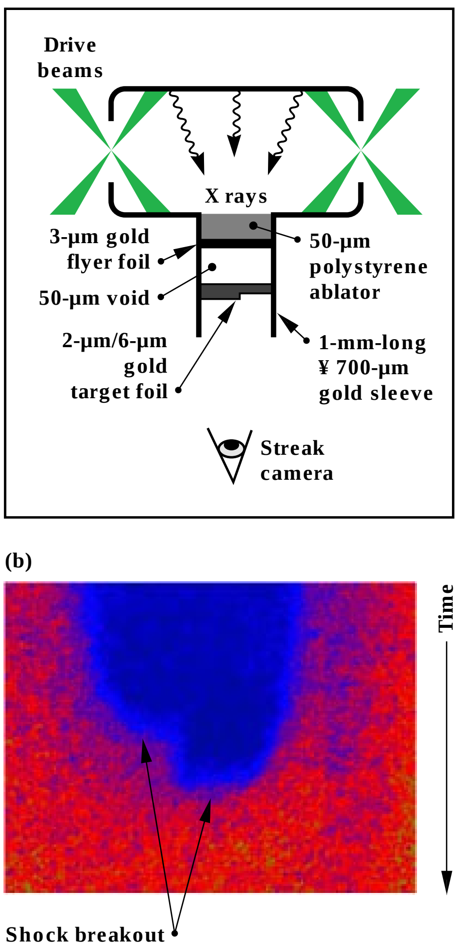



**Figure 6.** **(a) Schematic of a radiation-driven shock experiment. The x rays escape from a hole in the cylindrical gold hohlraum and ablate a 50-µm layer of polystyrene with a 3-µm gold flyer foil. The flyer foil accelerates through a 50-µm void, collides with a two-step gold target foil, and launches a compression wave in the target foil. (b) A typical streak camera image of a shock breakout showing the time interval between the two sides of the step.**

## Indirectly Driven Colliding Foil Experiments

To reach a regime of very high pressure without sacrificing laser spot size and one-dimensionality, we employ a variation of the well-known flyer-plate technique. In this technique, a flyer—in this case a foil—stores kinetic energy from the driver during an acceleration and rapidly delivers it as thermal energy when it collides with another foil. The flyer foil also acts as a preheat shield so that the target remains on a lower adiabat, that is, for a given pressure the temperature is kept lower than it would be if exposed to the driver.

In this type of experiment (Figure 6), the laser beams are focused into a millimeter-scale cylindrical gold hohlraum; the radiation that escapes from a hole in the hohlraum becomes the x-ray drive. The hohlraum x rays ablate a 50-µm layer of polystyrene with a 3-mm-thick gold flyer foil. This foil then accelerates through a void and, near the end of the laser pulse, collides with a stationary, two-step (two-thickness) gold target foil. The shock on the rear side of the target foil is then imaged with an optical streak camera.

Figure 6b is a typical streak camera image of shock breakout on a two-step target foil. The time interval between the two breakout times (one for each thickness) measures the shock speed in the target. An interval of 57 ps between breakout on the two steps corresponds to an average shock velocity of 70 km/s. According to our equation-of-state tables, this shock speed corresponds to a density of 90 g/cm$^3$ and a pressure of 0.74 Gbar in the gold target, which is *by far* the highest inferred pressure obtained in a laboratory.

In this experiment, any spatial imbalance in the drive or any unpredicted edge effects (for example, those from interactions between the flyer foil and sleeve containing the target assembly) could cause the flyer foil to tilt or curve and drive a nonplanar shock into the target. However, any nonplanarity would be readily observed because of the relatively large diameter of the foils; furthermore, any edge-induced nonuniformities would be minimized because the step in the target is at the center of the foil. (See pp. 28–29 for a discussion of this experiment relative to weapons physics equation-of-state experiments.)

If the target foil is preheated by high-energy x rays from the hohlraum before the flyer foil hits it, the measurement is compromised. To test this possibility, we altered the x-ray drive in one experiment so that the overall intensity would be identical to that in other experiments but the intensity of high-energy x rays (those ≥2.5 keV) would be reduced by more than a factor of five. The result indicated that the measurement was not affected by preheat.

## X-Ray Opacity Measurements

To understand the plasma state and radiative transport, we need to obtain high-quality measurements of the radiative opacity of materials. To do this, we must simultaneously measure the x-ray transmission, temperature, and density of a material sample in a single experiment. These measurements have been done successfully on Nova using point-projection spectroscopy (see Figure 7); we believe that this technique will be even more successful in similar experiments on NIF because we will be able to access larger ranges of material densities and temperatures.

When we use point-projection spectroscopy on Nova, we use eight laser beams to heat the sample. Then, a point source of x rays is produced by tightly focusing one of the remaining laser beams onto a small backlight target of high-*Z* material. X rays from the backlight pass through the sample onto an x-ray diffraction crystal and are then recorded on x-ray film. Other x rays from the same point bypass the sample but are still diffracted from the crystal onto the film record. The ratio of attenuated to unattenuated x rays provides the x-ray transmission spectrum of the sample. Proper collimation allows a highly quantitative analysis of the spectrum. Background from film chemicals, sample emission, and crystal x-ray fluorescence can all be separately determined from the x-ray film record.

The sample itself must be uniform in temperature and density. Uniformity of temperature is achieved by heating the sample in a hohlraum that does not allow laser light to reflect or impinge on it directly; thus, the sample is heated only by x rays. The hohlraum, by providing x-ray drive that volumetrically heats the sample that is tamped, also maintains the relatively high density of the sample and ensures that it is in local thermodynamic equilibrium.

The sample is tamped by plastic so that as it expands, its density remains constant. The thickness of the tamper is determined by calculations, and the density of the sample is determined by imaging. Usually, a second point-projection spectrometer images the expansion of the sample. The first point-projection spectrometer is used to measure the sample's absorption. The relative intensities of the transitions from the different ion species give the ion balance in the sample, which, when coupled to the density measurement, gives the temperature of the sample.

The two point-projection measurements allow density to be measured to an accuracy of ±10% and the temperature to an accuracy of about 5%. With these accuracies it is possible to make a quantitative comparison between the experimental results and the theoretical calculations of the opacity.

In one experiment on Nova, we measured the opacity of niobium in an aluminum–niobium sample. The sample contained 14% aluminum by weight for the temperature measurement. Figure 8 shows the transmission of the aluminum and the transmission of the niobium. The dotted lines overlaying the experimental data are the calculations. In general, there is excellent agreement. This experiment is a milestone. It shows that we can obtain opacity measurements accurate enough to serve as an *in situ* temperature diagnostic for the sample. The accuracy of the sample's temperature, measured to be 48 eV (±2 eV), represents a very important advance in measuring temperatures of high-energy-density matter. (See pp. 27–28 for a discussion of this experiment in relation to weapons physics opacity experiments.)

## Plasma Physics

In the broadest sense, plasma physics is the scientific investigation of the predominant state of matter in our universe, plasma. The study of plasma physics has been stimulated over the past four decades by its close

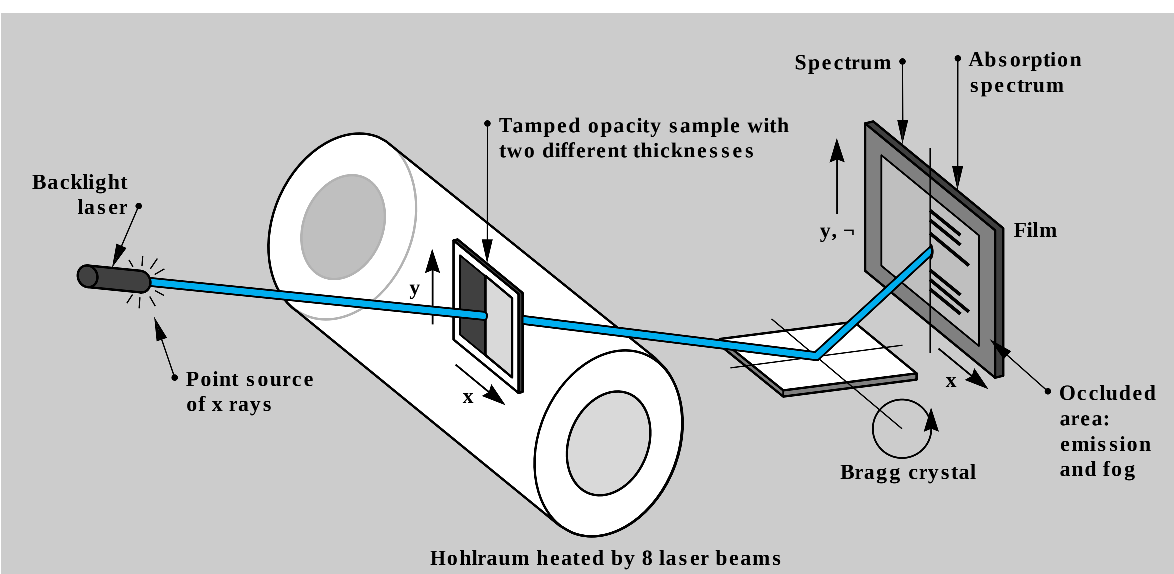



**Figure 7.** Schematic of point-projection spectroscopy for opacity measurements. The laser-produced backlight x rays pass through the target and are imaged. A Bragg crystal disperses the spectrum so that a spatially and spectrally resolved image is obtained. Temporal resolution is provided by backlight duration.

connection with the goal of creating fusion as an energy source and with the exploration of various astrophysical plasmas.

The advanced experimental capabilities of the NIF will allow us to produce and characterize large, hot, uniform plasmas. With large uniform plasmas, we will be able to measure electron and ion temperature, charge state, electron density, and flow velocity. In short, we will be able to perform a wide range of *quantitative* experiments on a medium that is a very good approximation of a real test bed for plasma physics. Many experiments will be extensions of the fusion energy experiments that have been performed on smaller, less powerful high-energy lasers. Many others, however, will go beyond the requirements of fusion energy to explore a range of basic topics in plasma physics, a few of which are discussed here.

## Filamentation

When a small hot spot, or speckle, in the laser-intensity profile undergoes self-focusing, filamentation occurs: that is, electrons (and eventually ions) are expelled from the filament, causing laser light to focus more tightly. This process, in turn, creates an unstable feedback loop; the more tightly focused the laser light is, the higher its intensity and the lower its electron density. Eventually, this instability is saturated by diffraction effects, thermal absorption, or parametric instabilities.

The growth of filamentary structures can be determined by the width and length of speckles in the incident laser beam. Because long speckles are more likely to self-focus than short speckles, filamentation can be described by a growth rate along the length of a speckle, or $8f^2l$, where f is the f-number of the beam (i.e., beam focal length divided by effective maximum beam diameter) and l is the wavelength of the laser light. If the speckle lengths are smaller than the scale length of the plasma, the f-number and the wavelength of the incident beam can be very powerful levers for modifying filamentation. By using large uniform plasmas on the NIF, we will be able to produce sufficiently large filaments to study this process over a wide range of wavelengths and f-numbers. We will also be able to explore this process over a broad range of experimental parameters by varying the color and f-number of the filamentation beam and by varying the plasma conditions (e.g., temperature, density, and average ion charge).

The primary diagnostic for filamentation would be the stimulated Raman scattering signal, which is indicative of the low density in the filaments. That could be coupled with high spatial-resolution imaging, high-resolution optical probing, and a study of the angular distribution of scattered light.

Thomson scattering could be used for these investigations to make highly localized measurements of plasma temperature and density. It could also be used to measure the coherent motion of electrons involved in ion acoustic and electron plasma waves. This measurement would provide a temporally and spatially resolved measure of the coherent fluctuation amplitude in a specific direction, as determined by the detector angle, the scattering volume, and the scattering light source. Measurement of the background fluctuation levels would provide information about the initial level of the coherent fluctuations, their amplification, and their saturation. It also could provide useful information about the coupling between stimulated Raman and Brillouin scattering if it were done at the same location and at the same time as the

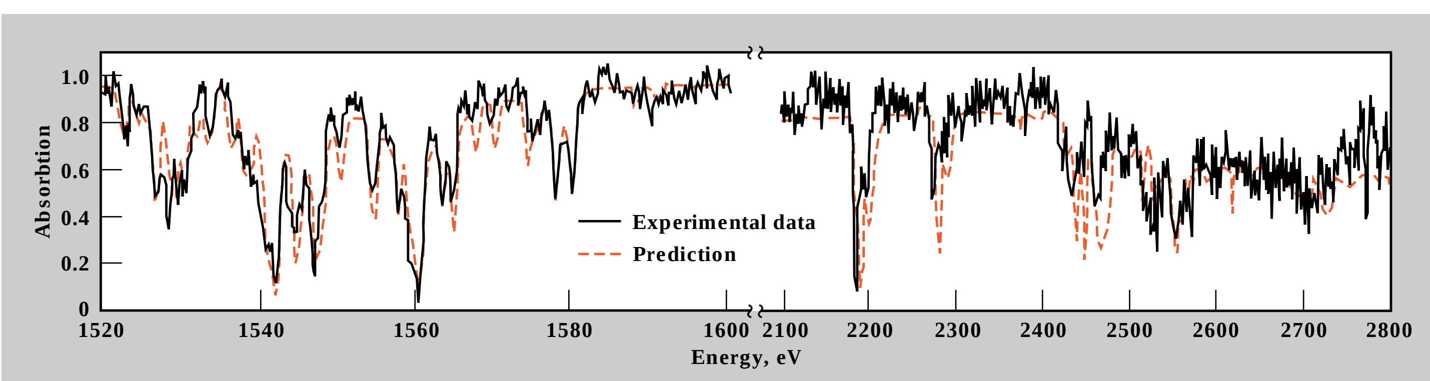



**Figure 8.** Absorption of an aluminum–niobium sample. The experimental data are in the solid black line and the opacity prediction is the dashed line. The spectrum of the aluminum-potassium alpha lines, which were verified to yield an accurate temperature, were measured on the same experiment as the niobium spectrum.

coherent motion measurements. Developing an x-ray Thomson scattering measurement to study coherent plasma motion in high density plasmas is another exciting possibility.

### Formation of Large, Uniform Plasmas

Presently, we can produce relatively high-temperature (3000-eV), millimeter-scale plasmas using the diagnostic complement and experiments shown in Figure 9. These large, uniform plasmas are used to study phenomena as diverse as plasma–laser interactions and nuclear reaction rates. The experimental geometry should be directly scalable to the NIF, with nine-tenths of the laser being used to form the plasma and one-tenth being used to create interactions. The ability to produce these large uniform plasmas on the NIF will allow us to study fundamental aspects of our experiments, such as hohlraum environments and sidescatter, that have been virtually impossible to interpret quantitatively.

### Short-Pulse, High-Power Experiments

There is widespread agreement that the NIF should include a beam line for short-pulse, high-power experiments. This capability is especially important for studying such basic topics as relativistic, ultra-high-intensity regimes of laser–matter interaction; high-gradient accelerator schemes; and fast ignition (Figure 10). It is also more amenable to detailed simulation and to systematic exploration of linear and nonlinear behavior of plasmas.

The high-gradient accelerator schemes employ plasmas that support much higher energy fields than those associated with conventional accelerator schemes. As a result, the device will be much more compact

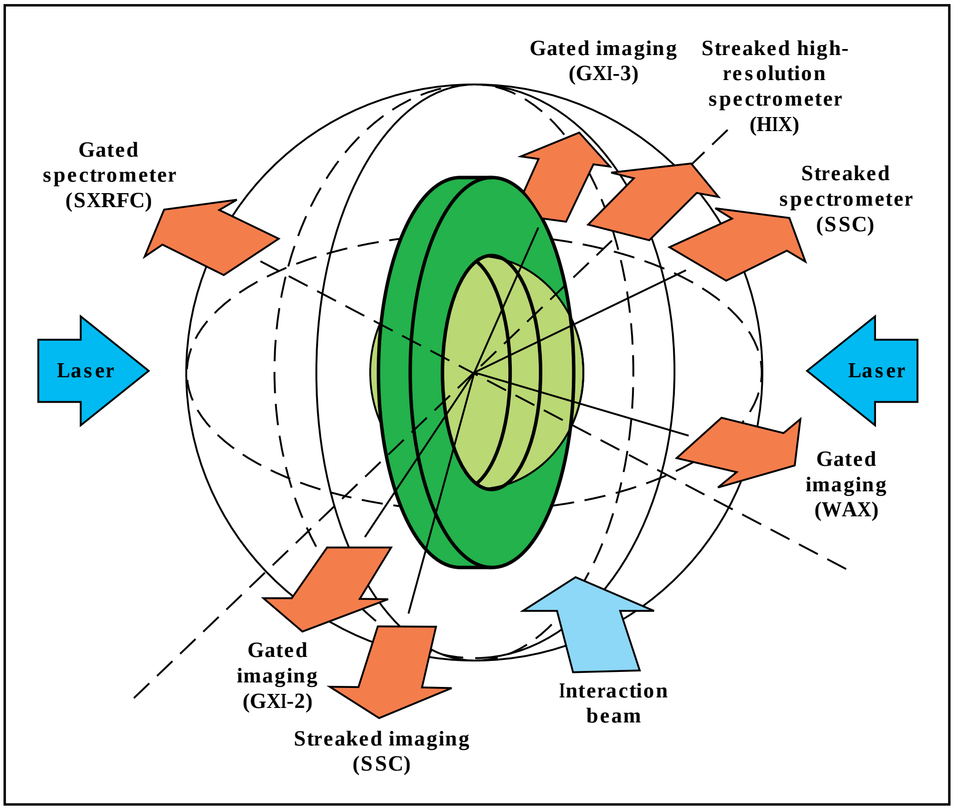



**Figure 9.** Schematic of the experiments and diagnostic complement (red arrows) used to form a large, hot, uniform plasma. A gas bag (light green) is filled through two tubes in the hoop (dark green). The pressure is stabilized by a pressure transducer that causes the fully ionized species to yield electron densities of approximately $10^{-1}$ cm$^3$. The roughly spherical plasma, which has a volume of 0.066 cm$^3$ and a radius of 2.5 mm, is heated to a temperature of about 3000 eV by heating lasers (blue arrows). A separate interaction beam (light blue arrow) drives the instabilities in a controlled way. This geometry should be directly scalable to the NIF.

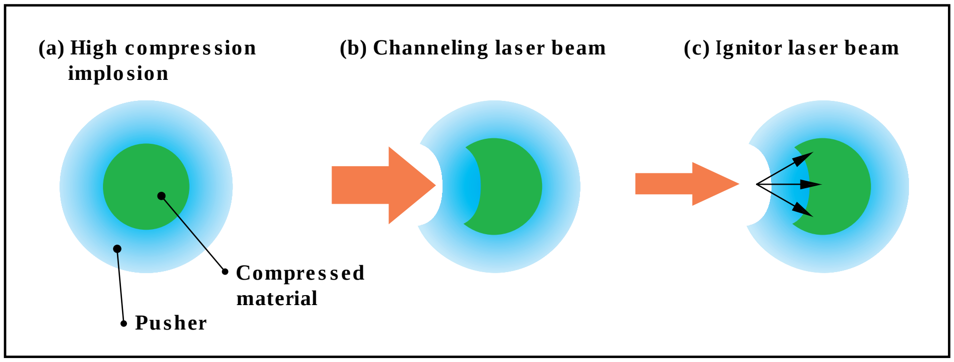



**Figure 10.** Fast ignition requires high compression, two laser systems, and system diagnoses. (a) In the first step of this process, a gas-filled sphere is imploded. The core of the compressed gas is at densities of 600 g/cm$^3$. (b) In the next step, a laser with a pulse duration of 100 ps and an intensity of $10^{18}$ W/cm$^2$ creates a channel by pushing the critical density surface toward the core. (c) Finally, the heater, or ignitor, beam is turned on. This beam interacts with the density gradient and generates hot electrons at MeV energies. These electrons penetrate into the core of the compressed gas and cause an instantaneous rise in the local temperature of the core.

and potentially cheaper. A number of novel schemes have been proposed and studied at laser powers not quite high enough to produce the desired electron velocity. If these schemes prove successful, applications to tunable sources of x rays are also envisioned.

## Radiation Sources

The conversion of laser energy into short wavelength radiation is a major goal of many high-energy laser experiments. On the NIF, we will be able to convert laser energy to a wide variety of x-ray and particle sources needed to address several important questions in basic and applied physics. For example, we will be able to produce intense broadband thermal x rays from high-*Z* targets, coherent amplified x rays (x-ray lasers) from high-gain plasmas, intense neutron pulses from implosion plasmas, and intense pulses of hard x rays from fast electrons. Accurate energy spectra and absolute measurements of the conversion of laser energy into all types of radiation and particle fluxes will play an important role in benchmarking our basic understanding of laser–plasma interactions and atomic physics.

Broadband x rays generated by NIF laser plasmas will be used to produce and characterize large, uniform plasmas relevant to inertial confinement fusion and astrophysics. The high temperatures and densities produced during implosion and subsequent ignition will be an excellent source of continuum x rays—those extending from the soft x-ray region to MeV with pulse durations of less than 100 ps.

Besides producing important coherent radiation sources (i.e., x-ray lasers), NIF will offer a critical test of our atomic modeling, allowing us to extrapolate existing neon-like and nickel-like collisional x-ray lasers to wavelengths of about 20 angstroms (Å = $10^{-10}$ m). At these wavelengths, we can use x-ray laser interferometry (the interference created by splitting and then recombining the x-ray laser beam) to measure electron densities in plasmas exceeding solid densities. Also, the short-pulse capability of the NIF may enable us to develop new x-ray lasers that emit radiation at wavelengths shorter than 10 Å; such bright, coherent sources would be very useful in characterizing solid matter for materials science and biophysics research.

The NIF will be able to generate more than $10^{18}$ neutrons in a single 100-ps pulse, making it very useful for producing uniform, high-density, low-temperature plasmas. It will be able to generate fast electrons with hundreds of kiloelectron volts in energy—which is a potential source of high-energy x rays for backlighting and probing plasmas.

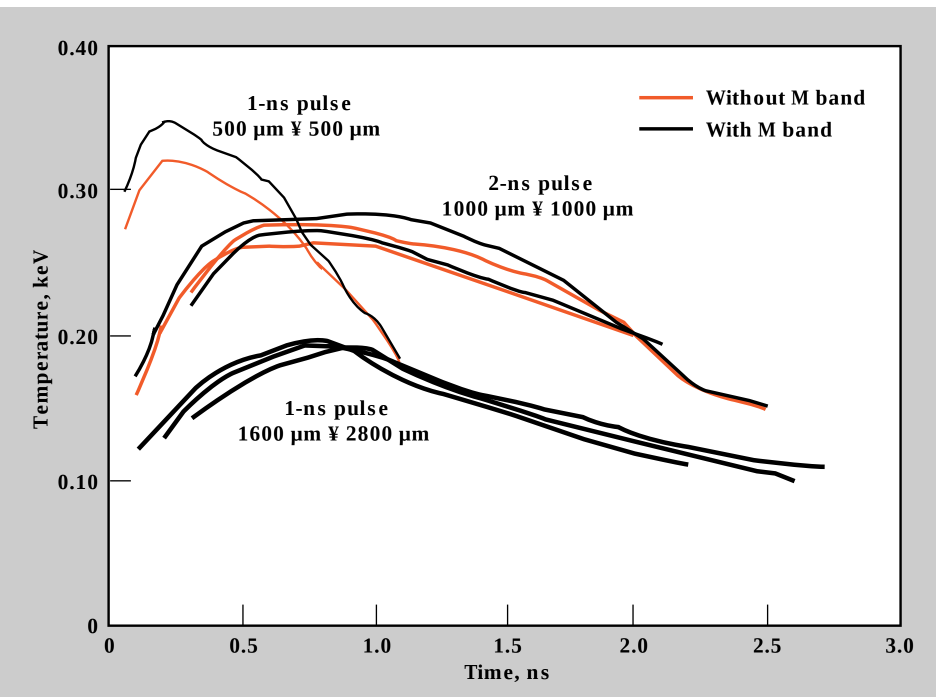



**Figure 11.** Equivalent radiation temperature vs time for three gold hohlraum experiments performed on Nova. The experiments used a total energy of 18 kJ. Laser entrance holes were in the sides of the 500- and 1000-µm-length hohlraums and through the ends of the 2800-µm-length hohlraum. The curves for each hohlraum show the reproducibility of the data. The black line indicates the equivalent radiation temperature with the M band; the red line indicates the equivalent radiation temperature without the M band. The contribution of the M band to the radiation temperature was greatest in the small hohlraums because of the closure of the holes; it was very small in the large hohlraums because they were large and because their viewing angle did not accommodate a view of the laser-irradiated spots.

These radiation sources are supplemented by the possibility of using radiation enclosures, or hohlraums (such as those shown in Figure 11), to generate radiation environments and x-ray drive fluxes. These sources will be able to produce far in excess of the approximately 200 eV produced by hohlraum sources available on current high-energy lasers. These sources will be of higher effective temperature and also will be able to provide uniform x-ray drive over far larger areas than is possible with today's sources. Thus, the advantages of using x-ray heating for the study of hot, dense matter will be greatly enhanced on the NIF.

## Radiative Properties

The importance of radiative properties in high-energy-density plasma derives from three factors:

- First, the radiative property can be the best indicator of the level of scientific knowledge in a particular area. For example, when scientists want to develop new descriptions of atomic structure, they look at transition energies.
- Second, radiative properties serve as primary data for numerous other studies. For example, spectral line lists are inadequate for many of the charge states of heavier elements. Thus, scientists measure and categorize the energies of highly ionized species for a variety of uses.
- Third, radiative properties serve as noninterfering probes. For example, by looking at the emission or absorption spectrum of a plasma, scientists can obtain fundamental information about the plasma's ionization balance, rate processes, densities, temperatures, and fluctuation levels. The radiative properties are therefore a powerful diagnostic of the plasma state.

Experiments on high-energy lasers have done much to enhance our knowledge of the radiative properties of hot, dense matter; thus, we expect that experiments on the NIF, such as those employing interferometry and plasma spectroscopy, will advance that knowledge even further.

### Interferometry Experiments

For years, optical probing of high-density or large plasmas has been difficult because of the high absorption of the probe, the effects of refraction, and the impossibility of going beyond critical densities. Recently, we did an experiment to see whether an optical measuring device, known as a Mach-Zehnder interferometer, and a standard 3-cm-long yttrium x-ray laser could be used to probe these plasmas more successfully.

In this experiment (shown schematically in Figure 12), the output from a standard 3-cm-long yttrium x-ray laser was collimated by a multilayer mirror and injected into the interferometer. An imaging optic from the interferometer then imaged a plane within the interferometer where a plasma was produced. Figure 13 shows the recorded interferogram of the plasma. The fringes, or contrast modulations, due to the plasma are clearly visible, indicating the feasibility of this technique. However, plasma blow-off, evident in the central region of the image, completely obscures the laser, indicating that the technique still has its limits. On the NIF we will be able to push the x-ray laser interferometer to shorter x-ray laser

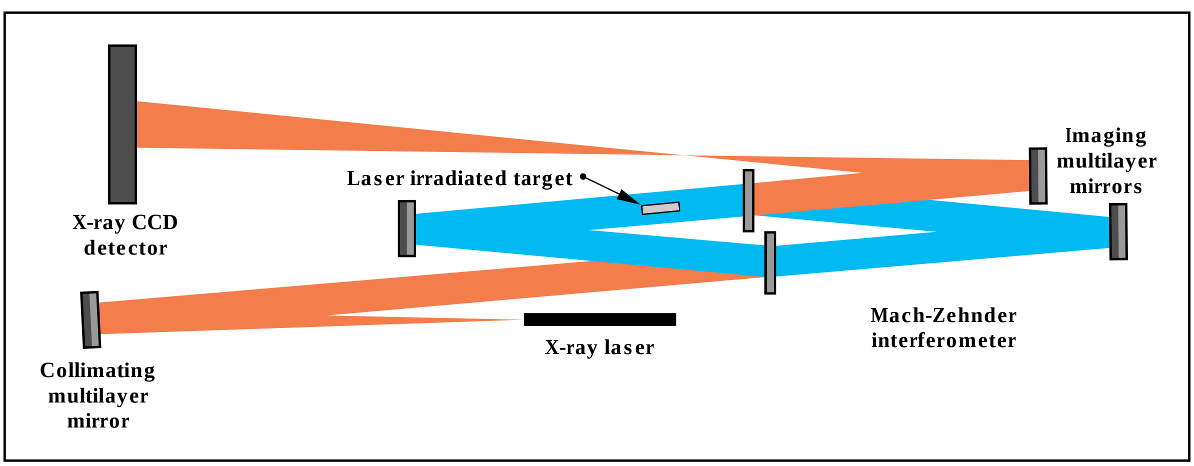



**Figure 12.** Schematic of the experimental setup for x-ray laser interferometry.

wavelengths, making it an even more important diagnostic tool in the study and characterization of large-scale plasmas.

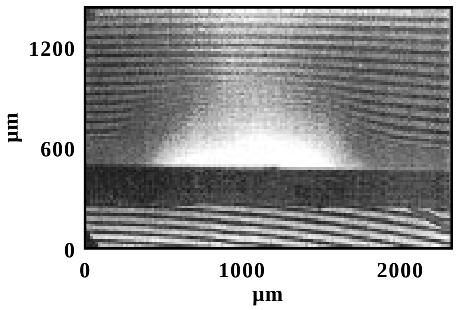
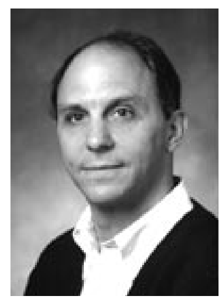



**Figure 13.** **Interferogram of a high-density plasma produced by x-ray laser interferometry. The plasma is made by irradiating the surface of a mylar plastic sample (solid horizontal band) with an x-ray beam. The bright spot above the plastic sample is the self-emission of the plastic.**

## Summary

The extraordinary range of physical conditions that will be achievable on the NIF will advance knowledge in the physical sciences. It will give us the ability to synthesize and analyze the plasmas that characterize the stellar environment during its evolution. It will enable us to investigate a number of stable and unstable flow problems under conditions that cannot be obtained by conventional means, such as wind tunnels, shock tubes, or other high-energy lasers. It will give us the ability to investigate material behavior at pressures from 1 to 100 terapascals and temperatures up to a few hundred electron volts so that we can validate our theoretical understanding of material behavior at extreme conditions. We will be able to convert NIF laser energy to a wide variety of x-ray and particle sources needed to address important questions in basic and applied physics. Finally, the NIF will enable us to push the x-ray laser interferometer to shorter x-ray laser wavelengths, making it an even more important diagnostic tool in the study and characterization of large-scale plasmas. The NIF will allow us to explore a previously inaccessible region of physical phenomena that could validate our current theories and experimental observations and provide a foundation for new knowledge.

**Key Words:** astrophysics; high-pressure physics; hydrodynamics; National Ignition Facility—high-energy laser experiments; plasma physics; radiation sources; radiative properties.



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# NIF Environmental, Safety, and Health Considerations

***The proposed NIF has been rated by the DOE as a radiological low-hazard, non-nuclear facility. Our analysis to date of environmental, safety, and health issues related to the NIF, presented in documents that are available to the public, shows that the system will have no significant environmental impact and present no significant safety or health risk to the work force and the general public.***

ENVIRONMENTAL, safety, and health (ES&H) considerations are of paramount importance in all phases of the design of the National Ignition Facility (NIF). From the outset, maximizing public and employee safety and minimizing health risk and environmental impact have been integral parts of the design process. In a broader sense, inertial confinement fusion has long-term potential as a source of future energy for the world. Earning the trust of the public and operating in a manner that protects the environment over time are requirements for any future energy source.

This article describes the results of environmental analyses as well as safety and health assessments. The topics fall broadly into three categories presented in the following order: radiation exposure, waste generation, and fusion targets.

The NIF will maintain a small inventory of less than 300 curies (0.03 grams) of tritium fuel and unburned tritium from inertial confinement fusion experiments. The fusion reactions in the 1-mm capsule will release a neutron for every tritium atom consumed, about $10^{17}$ atoms for an ignition experiment. The NIF target area employs heavy shielding, including 2-meter-thick concrete walls and a shielded vessel against the radiation. We have estimated the routine annual radiation dose at the site boundary, the maximum annual dose and average annual dose to any NIF worker, and the effects of a worst-case accident assuming release of the maximum planned tritium inventory. We have also estimated the quantities of hazardous, mixed, and low-level radioactive wastes. Before turning to these matters, a brief overview of the review process will help to put our efforts to date into perspective.

## The Assessment and Review Process

Safety and environmental analysis specific to the NIF began more than two years ago. This work was an outgrowth of continuing environmental impact and safety analyses of general concepts for future inertial confinement fusion (ICF) facilities. More than a year ago, a standing NIF working group was formed at LLNL. The group is made up of environmental and safety experts in radiation protection, safety analysis, environmental evaluation, laser operations, occupational safety, tritium handling, waste handling, quality assurance, and fire protection. The group meets biweekly to ensure consistent and well-documented evaluation of environmental and safety aspects of the NIF design.

The NIF working group has prepared the Preliminary Hazards Analysis for the NIF[1] as well as radiation protection,[2] safety, environmental, quality assurance, and decommissioning evaluations of the NIF design.[3] These analyses are available to the public as published reports.[4]

ES&H issues are extensively analyzed by experts, documented, and reviewed by the public as part of the process established by the DOE for major system acquisitions such as the NIF. Whereas major steps toward safety and environmental analyses have already been done for NIF, additional analyses will include an Environmental Impact Statement, Preliminary and Final Safety Analyses, and Operational Readiness Reviews. The DOE requires all of these studies to ensure that essential aspects of the project are thoroughly analyzed and are completely satisfactory before operations begin.

## Radiation Doses

In our radiological assessments, the unit of measure is the rem, which stands for roentgen-equivalent in man and is a unit of biological radiation dose. It is the amount of ionizing radiation that produces the same damage to humans as 1 roentgen of high-energy x rays. Natural background radiation from the environment—that is, from naturally occurring elements, cosmic radiation, and so forth—averages 0.3 to 0.5 rem/yr depending on where an individual lives. This natural background radiation does not include exposure to other potential sources of radiation, such as that from airplane flights and some types of medical diagnoses or treatments.

The routine annual dose from NIF at a site boundary 300 meters from NIF is expected to be 0.00013 rem. Put into perspective, this value represents 0.13% of the DOE and Environmental Protection Agency guideline and is 350 times less than the annual radiation dose arising from emissions from a 1-$GW_e$ coal-fired power plant.

The average annual dose received by flight attendants is 0.5 rem, a dose not monitored by the airline industry. In comparison, the *maximum* annual dose to any NIF worker will be less than 0.5 rem, which is less than 10% of the DOE guidance. The *average* dose to any NIF worker is estimated to be about 0.01 rem.

The maximum tritium inventory for the NIF will be 300 curies (Ci). This amount is the equivalent of 0.03 grams of tritium. The maximum NIF inventory is less than 3% of the routine inventory of the National Tritium Labeling Facility in Berkeley, California, which uses tritium for tagging biomedical samples. One NIF target will contain less that 2 Ci of tritium, one-fifth the amount of tritium in some typical theater exit signs of which more than one million are sold annually.

There are no significant radioactive or hazardous effluent levels for NIF. For example, the projected maximum emission of tritium is less than 10 Ci/yr, the equivalent of the tritium in a single exit sign. The dose to a member of the public expected from all NIF effluents is 600 times less than that from a single cross-country airline flight.

The worst-case accident considered in our safety assessment assumes the release of all the tritium (300 Ci) in its worst biohazardous form (tritiated water) immediately after a maximum-yield experiment (20 megajoules). This postulated, but highly unlikely, accident would result in a calculated dose of 0.056 rem at a site boundary 300 meters from NIF. This dose is 0.2% of the DOE siting guidelines for annual exposure.

## Waste Generation

NIF will generate three types of waste: hazardous, low-level radioactive, and mixed (a combination of hazardous and low-level radioactive). To be on the conservative side, we estimated higher waste quanlities than are likely from the NIF's waste streams. Moreover, our assessment has not fully considered waste-minimization techniques, such as frozen carbon dioxide pellet cleaning. Waste minimization will be an important and continuing design activity.

The annual hazardous waste stream associated with NIF will be about 3180 kg (7000 lb) of solid waste and 2270 L (600 gal) of liquid waste.[3] Most of this waste stream, about 2270 kg (5000 lb), will be in the form of 20 boxes of paper soaked with capacitor oil. Such waste is similar to but smaller in quantity than that generated in the same time by an automobile oil-changing facility. The waste will be routinely disposed of by certified contractors.

Mixed waste is both radioactive and chemically hazardous. The annual mixed waste stream associated with NIF will be about 135 kg (300 lb) of solid and about 2000 L

(530 gal) of liquid,[3] which represent a small fraction of the quantities currently generated at LLNL. These mixed waste quantities take into consideration some use of frozen $CO_2$ pellet cleaning, a dry, high-pressure scouring technique that decontaminates objects and avoids the need for alternate methods that use hazardous liquid solvents, thereby generating large quantities of liquid mixed waste.

The annual solid low-level radioactive waste stream, 400 kg (850 lb), will be a small fraction of the quantity currently generated at LLNL and is less than one-sixth of that produced by a major university's medical center. The annual liquid low-level radioactive waste stream (aqueous waste) will be disposed of in several 55-gallon drums,[3] along with two drums of vacuum pump oil, according to applicable guidelines.

## Fusion Targets

ICF targets are used in many facilities throughout the country. Examples of current or future facilities using such targets include the Nova laser; the Particle Beam Fusion Accelerator II (PBFA-II) at Sandia National Laboratory in Albuquerque, NM; the planned upgrade of the Omega laser at the University of Rochester; and the proposed NIF. The manufacture and filling of fusion fuel capsules is a separate and ongoing activity of the national ICF Program that supports present and future facilities. These functions are carried out at several DOE and commercial sites (for example, at General Atomics in La Jolla, CA; the University of Rochester in Rochester, NY; Los Alamos National Laboratory in Los Alamos, NM; and LLNL).

The filling activity for NIF targets requires a total inventory of less than 5 grams of tritium. The target manufacturing and filling facilities have their own *National Environmental Policy Act* (NEPA) documentation and engineered systems to protect workers, the public, and the environment by safely confining any tritium.

Because of the existing national capability, the NIF project will not include a dedicated target manufacturing and tritium filling facility. Instead, it will receive several types of targets from several different sites. Targets for NIF will be transported in certified containers prescribed by the Department of Transportation and in accordance with the *Code of Federal Regulations* (Title 49, section 173).

## Summary

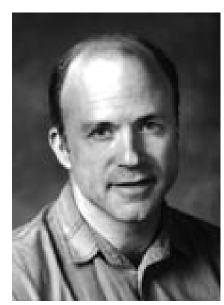
After reviewing the Preliminary Hazards Analysis report, the DOE concurred with the preliminary categorization of the NIF as a radiological low-hazard, non-nuclear facility. This means that operation of the NIF will have minor onsite and negligible offsite consequences. The hazards categorization will be reviewed in each subsequent safety analysis report.

The conservative safety and environmental analyses outlined in this article are the first of a series of studies required to ensure the safety of workers, the public, and the environment. The NEPA process of the DOE ensures joint participation by the public and those states that may be affected by the project. The Environmental Impact Statement process will also allow participation by the public in reviewing the potential environmental impacts of the NIF.

**Key Words:** environmental safety and health (ES&H); National Ignition Facility (NIF)—radiation dose; tritium inventory; waste stream.

**Notes and References**


1. S. J. Brereton, *Preliminary Hazards Analysis for the National Ignition Facility*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-ID-116983 (1993).
2. M. S. Singh, *Radiological Analysis of the National Ignition Facility*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-LR-115188 (1993).
3. *National Ignition Facility Conceptual Design Report*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-PROP-117093 (1994) and *National Ignition Facility Seting Proposal–LLNL*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-PROP-119353 (1994).
4. To obtain copies of references 1 and 2, contact the National Technical Information Services (NTIS), U. S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161. Reference 3 cites ongoing documents that will not be available to the public through NTIS until complete; copies, however, are available to read at the Livermore Public Library, Livermore, CA, and at the Visitors Center at LLNL.
5. S. Brereton, G. Greiner, M. Singh, and M. Trent also contributed to this article.

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## A Tour of the Proposed National Ignition Facility

When built, the National Ignition Facility (NIF) will house the world's most powerful neodymium glass laser system. NIF will be 50 times more powerful than the Laboratory's Nova laser, currently the world's most powerful. The NIF will contain 192 independent laser beams, or "beamlets," each with a square aperture of a little less than 40 cm on a side. For economy and efficiency, beamlets will be stacked four high and twelve wide into four large arrays. The beamlines will require more than 9000 large-format optics (greater than 40 × 40 cm) and several thousand smaller optics. Compared to the size of the current Nova facility at LLNL, which uses a single-pass amplifier laser architecture, the compact multipass design of the proposed NIF system allows us to put a laser with a typical output that is 40 times greater than Nova's into a building only about twice the size. This article follows the path of a photon from the master oscillator and preamplifier, through the NIF main laser components, to the target. It also highlights some of the development efforts, begun many years ago, for components, such as the multipass glass amplifiers and plasma electrode Pockels cell, that allow us to design a large, multipass glass laser economically and at very low risk. Results from our recently completed Beamlet Demonstration Project, involving a prototype NIF beamline, along with the models and design codes we are testing ensure that we can have great confidence in the performance projected for NIF.

**Contact: John R. Murray (510) 422-6152.**

## NIF and National Security

Since the end of the Cold War with the demise of the Soviet Union, the U.S. nuclear weapons program has changed dramatically. A major change has been the moratorium on underground nuclear testing, which is likely to be extended indefinitely by a Comprehensive Test-Ban Treaty. Although there are now far fewer weapons and weapon types than only a few years ago, the nuclear stockpile nevertheless remains, and U.S. policy will continue to rely on nuclear deterrence for the foreseeable future. Because the U.S. must be confident that the nuclear arsenal would perform reliably if needed, reliance on testing to assess weapon performance must be replaced by reliance on thorough scientific understanding and better predictive models of performance—that is, science-based stockpile stewardship.

The National Ignition Facility (NIF) will enable us to produce energy densities (energies per particle) that overlap with the energy densities produced in nuclear weapons, yet the total energy available on NIF will be a minuscule fraction of the total energy from a weapon. This combination of low total energy with weapons-regime energy density will allow us to pursue, besides ignition experiments, many nonignition experiments. These will allow us to improve our understanding of materials and processes in extreme conditions by isolating various fundamental physics processes and phenomena for separate investigation. Such studies will include opacity to radiation, equations of state, and hydrodynamic instability. In addition to these, we will study processes in which two or more such phenomena come into play, such as in radiation transport and in ignition.

Weapons physics research on NIF offers a considerable benefit to stockpile stewardship, not only in enabling us to keep abreast of issues associated with an aging stockpile, but also in offering a major resource for training the next generation of scientists who will monitor the stockpile.

**Contact: Stephen B. Libby (510) 422-9785.**

## The Role of NIF in Developing Inertial Fusion Energy

The proposed National Ignition Facility (NIF) will provide LLNL researchers as well as others in the scientific community committed to developing Inertial Fusion Energy (IFE) with the means of developing and testing data and materials that are key to the long-term goal of building and operating IFE power plants as clean, viable, environmentally safe sources of inexhaustible energy. When the NIF demonstrates fusion ignition, which is central to proving the feasibility of IFE, it will tell us much about IFE target optimization and fabrication, provide important data on fusion-chamber phenomena and technologies, and demonstrate the safe and environmentally benign operation of an IFE power plant. In accomplishing these tasks, the NIF will also provide the basis for future decisions about IFE development programs and facilities, such as the planned Engineering Test Facility (ETF). Furthermore, it will allow the U.S. to expand its expertise in inertial fusion and supporting industrial technology as well as promote U.S. leadership in energy technologies, provide clean, viable alternatives to oil and other polluting fossil fuels, and reduce energy-related emissions of greenhouse gases.

**Contact: B. Grant Logan (510) 422-9816 or Michael T. Tobin (510) 423-1168.**

## Science on the NIF

Last March, a group of scientists convened at the University of California, Berkeley, to discuss the potential scientific applications of the National Ignition Facility (NIF)—a 192-beam, neodymium glass laser that will be used to obtain the high-energy physics data needed to maintain the nation's nuclear stockpile. The objective of the gathering was to identify areas of research in which the NIF could be used to advance knowledge in the physical sciences and to define a tentative program of high-energy laser experiments. The scientists determined that the most effective scientific applications of the NIF would be in astrophysics, hydrodynamics, high-pressure physics, and plasma physics. In astrophysics, the NIF would give scientists the ability to synthesize and analyze the plasmas that occur at all stages of stellar evolution. In hydrodynamics, it would enable them to investigate flow problems under conditions that cannot be obtained by the conventional wind tunnel or shock tube. In high-pressure physics, it would allow scientists to investigate material behavior at pressures from 1 to 100 terapascals and temperatures up to a few hundred electron volts so that they could validate their theoretical models of material behavior. Scientists would also be able to convert NIF laser energy to a wide variety of x-ray and particle sources needed to address important questions in basic and applied physics.

With the NIF, scientists could push the x-ray laser interferometer to shorter x-ray laser wavelengths so that it would be a more valuable diagnostic tool in the study and characterization of large-scale plasmas. In short, the NIF would enable scientists to explore a previously inaccessible region of physical phenomena that could validate their current theories and experimental observations and provide a foundation for new knowledge of the physical world.

**Contact: Richard W. Lee (510) 422-7209.**

## NIF Environmental, Safety, and Health Considerations

To ensure the safety of workers and the public and to assess potential environmental impacts, we have completed the first of a series of safety and environmental analyses related to the proposed National Ignition Facility (NIF). On the basis of its review of the Preliminary Hazards Analysis report, the DOE has concurred with the categorization of the NIF as a radiological low-hazard, non-nuclear facility. Our studies to date show that the NIF will present no significant environmental or health and safety risk. For example, the average annual biological radiation dose to a NIF worker is estimated to be about 0.01 rem. This value is less than 10% of the DOE guideline. As part of the *National Environmental Protection Act* (NEPA) determination process established by the DOE, the public will be invited to participate in reviewing environmental, safety, and health issues related to the NIF.

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